BEYOND BOUNDARIES: UNVEILING HUMAN-DRONE PROXEMIC DYNAMICS USING VIRTUAL REALITY

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Abstract

Social drones—autonomous unmanned aerial systems operating in inhabited environments—are a rapidly developing transformative technology. While they promise significant benefits, their successful integration into everyday life depends not only on technological advancements but also on their harmonious incorporation into people's environments. Individuals intuitively navigate their surroundings, adjusting their distances from both people and non-living entities. This raises a critical question: How will the integration of social drones affect these subtle spatial dynamics? Inappropriate spacing can lead to discomfort, stress, and even defensive reactions, such as evasive maneuvers or attacks. Therefore, before drones are deployed in inhabited spaces, it is essential to understand their spatial relationships with people—an area of study known as human–drone proxemics (HDP). Despite the importance of this issue, significant gaps remain. First, there is a lack of theoretical frameworks for interpreting human–drone proxemics. Second, there is an absence of valid methodological approaches, largely due to constraints in real-world studies. To address these gaps, this research aims to: 1) provide researchers with essential interpretive tools by establishing a solid theoretical foundation for human–drone proxemics, and 2) develop an effective approach for studying these behaviors by investigating Virtual Reality (VR) as a promising alternative to real-world studies. Following an extensive literature review on proxemics, Human–Drone Interaction (HDI), and VR, we devised a course of action. Through five user studies conducted in virtual environments specifically designed for studying proxemics, we evaluated the applicability of four frameworks that explain people's spatial relationships with drones. Each study included theoretical grounding, empirical assessments, drone design considerations, and concrete guidelines for adopting these frameworks. Our findings reveal that distancing behaviors with external entities are shaped by various motivations—including goal-oriented actions, protective instincts, social appropriateness, and arousal regulation. These motivations, influenced by how individuals perceive sensory information, often conflict, prompting physical, environmental, or cognitive adjustments to reconcile competing desires, such as the urge to approach the drone while maintaining distance. These insights culminated in a model of human proxemics with external entities, grounded in human–drone proxemics but extendable to other entities, integrating diverse motivations, highlighting their interactions, and offering new insights into the sensory processes underlying these behaviors. It equips researchers with a framework to better motivate, predict, and interpret findings in HDP studies. Additionally, our research developed a practical understanding of VR as a methodological tool for exploring HDP. VR proved to be a powerful approach, offering significant advantages over constrained real-world studies. We formulated a methodological protocol and practical guidelines to equip researchers with the tools they were lacking, enabling more effective exploration of human–entity proxemics. These contributions not only fill critical gaps in the field but also provide a robust foundation for future research, fostering cumulative knowledge development in HDI.

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When I began this research journey, I didn't anticipate finding fellow travelers whose advice, support, and companionship would keep me on the right path, shaping my decisions and fueling my determination. This section is an ode to their help.

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Declaration and Contributing Publications

I declare that, except where explicit reference is made to the contribution of others, that this dissertation is the result of my own work and has not been submitted for any other degree at the University of Glasgow or any other institution.

The work presented in this thesis has contributed to research publications in leading conferences (e.g., CHI, INTERACT) and journals (e.g., IJSR, THRI).

Study #1 discussed in chapter 3, led to a Late-Breaking Work presented at the CHI 2022 conference [58]. This work was later expanded into a full journal paper with a detailed qualitative analysis, published in the International Journal of Social Robotics (IJSR) in 2024 [57].

Extended Abstract, *CHI (2022)*

Robin Bretin, Emily S. Cross, and Mohamed Khamis. 2022. Co-existing With a Drone: Using Virtual Reality to Investigate the Effect of the Drone's Height and Cover Story on Proxemic Behaviours. In Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems (CHI EA '22), 1–9. https://doi.org/10.1145/3491101.3519750

Journal Paper, *International Journal of Social Robotics (2024)*

Robin Bretin, Emily Cross, and Mohamed Khamis. 2024. Co-existing with Drones: A Virtual Exploration of Proxemic Behaviours and Users' Insights on Social Drones. International Journal of Social Robotics. https://doi.org/10.1007/s12369-024-01111-7

Study #3 detailed in chapter 4 was presented at the INTERACT 2023 conference, where it received two awards: **Best Paper by a Doctoral Student** and the **Reviewer's Choice Award**.

Conference Paper, *INTERACT (2023)*

Robin Bretin, Mohamed Khamis, and Emily Cross. 2023. "Do I Run Away?": Proximity, Stress and Discomfort in Human-Drone Interaction in Real and Virtual Environments. In Human-Computer Interaction – INTERACT 2023 (Lecture Notes in Computer Science), 525–551. `https://doi.org/10.1007/978-3-031-42283-6_29`

Study #2 presented in chapter 3, has been accepted for publication in the ACM Transactions on Human-Robot Interaction.

Journal Paper, *ACM Transactions on Human-Robot Interaction (2025)*

Robin Bretin, Mohamed Khamis, Emily Cross, and Mohammad Obaid. 2025. The Role of Drone's Digital Facial Emotions and Gaze in Shaping Individuals' Social Proxemics and Interpretation. J. Hum.-Robot Interact. `https://doi.org/10.1145/3714477`

Other Publications: In addition to the work included in this thesis, I collaborated on several other research projects. These collaborations, while not directly part of the thesis, significantly contributed to broadening my expertise in areas such as study design, virtual reality implementation, qualitative analysis, and academic writing. Below is a selection of these publications (see Google Scholar for a full list):

Extended Abstract, *CHI (2022)*

Kieran Watson, Robin Bretin, Mohamed Khamis, and Florian Mathis. 2022. The Feet in Human-Centred Security: Investigating Foot-Based User Authentication for Public Displays. In Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems (CHI EA '22). Association for Computing Machinery, New York, NY, USA, Article 441, 1–9. `https://doi.org/10.1145/3491101.3519838`

Conference Paper, *IDC (2023)*

Cristina Fiani, Robin Bretin, Mark Mcgill, and Mohamed Khamis. 2023. Big Buddy: Exploring Child Reactions and Parental Perceptions towards a Simulated Embodied Moderating System for Social Virtual Reality. In Proceedings of the 22nd Annual ACM Interaction Design and Children Conference (IDC '23). Association for Computing Machinery, New York, NY, USA, 1–13. `https://doi.org/10.1145/3585088.3589374`

Chapter 1

Introduction

1.1 Motivation

In today's rapidly evolving technological landscape, transformative innovations are significantly altering our way of life. The progression from raw concepts to seamlessly integrated devices involves iterative refinement and a deep understanding of both the technology and the people it serves. Throughout this process, both technology and society evolve, marking a clear distinction between the past and the present. Social Drones, defined as autonomous unmanned flying artificial systems operating in inhabited environments, exemplify a potentially transformative technology in its early, burgeoning stages of development.

The Conditional Advent of Social Drones As we master terrestrial technologies, we encounter the limitations imposed by spatial saturation and the complexities arising from numerous actors vying for space. Drones offer a solution by inviting us to explore and shape the uncharted realms above. Leveraging their ability to reach any location and carry sensors or other objects, drones are already being utilized in various commercial applications, including construction [16, 231], policing [116], firefighting [18, 206], agriculture [2], delivery [136], and more [173]. While they are mostly controlled by trained pilots and act as extensions of these operators, advancements in artificial intelligence and improvements in battery life and sensors suggest that autonomous drones will soon be widely deployed. This opens up a broad field of novel potential applications [173], including personal security [207], flying assistants, domestic drone [270], and even social roles such as companionship [141, 200] and emotional support [124]. Baytas and colleagues [38] argue that autonomous entities like drones inevitably initiate social interactions when perceived by humans, thereby acquiring a social dimension themselves. This broad definition extends the consideration of the social dimension to any kind of autonomous machine, even if their primary function is not social in nature. Consequently, autonomous drones operating in inhabited environments such as homes or cities are interchangeably referred to as "Social Drones".

Yet to ensure the seamless integration of social drones into society, enhance well-being, and mitigate potential adverse effects, it is imperative to understand how individuals perceive and interact with them. This understanding is crucial for designing drones in a manner that aligns with societal and human needs and expectations. Autonomous drone's design entails various dimensions, encompassing not only the drone's appearance but also its behavioral characteristics [38].

The Proxemic Challenge As social drones are anticipated to interact closely with humans, akin to everyday human interactions, understanding the spatial dynamics between these machines and individuals becomes paramount.

This subconscious and dynamic process of regulating distances with entities in our surroundings is termed Proxemics, a concept introduced by Edward T. Hall and eloquently described as "The Hidden Dimension" of human social interactions [163]. Proxemic behaviors serve as key social cues, conveying nuanced information about individuals and their relationship with their environment. The interpersonal distance between individuals reflects their intimacy levels and, when coupled with other social cues like gaze and posture, communicates specific social messages. However, proxemic behaviors are multifaceted, serving various functions beyond mere social interaction [11,96], with other driving mechanisms involved [167]. For instance, someone might maintain a safety distance from a hornet flying in a room to stay safe, change seats on a train to avoid a noisy child disrupting their focus, or maneuver swiftly through a crowd to catch a train on time. Importantly, inappropriate proxemic behaviors can induce stress and discomfort, with even greater magnitude when perpetrated by robots [311]. The ability to anticipate the proxemic behaviors of others also empowers us to dynamically adjust our navigation tactics or actions, thereby averting potentially hazardous situations. For instance, this could involve refraining from startling someone near a precipice or yielding to someone visibly rushed before proceeding with delicate cargo.

For these reasons, proxemics presents a critical design challenge for autonomous drones [38], as inappropriate proxemic approaches may precipitate adverse repercussions for individuals, ranging from discomfort to potential physical harm. However, as of yet, there remains a significant lack of comprehensive understanding into the underlying motivations driving individuals' proxemic behaviors in the vicinity of drones. This gap notably complicates the rationale behind specific design decisions and the interpretation of observed behaviors in user studies, while also hindering applications that rely on close proximity [27, 75] to succeed. It is essential to understand **what motivates individuals' proxemic behaviors around them and how these behaviors manifest** (Research Question 1).

Building Proxemic Foundations Research on Human–Robot Proxemics (HRP) has so far lacked sufficient theoretical foundations [227], often focusing too heavily on the communicative function while neglecting others. Drones present a novel interaction paradigm with specific characteristics that necessitate considering them as a unique entity, thus defining the new field of Human–Drone Proxemics (HDP). Recognizing that the lack of theoretical foundations has impeded the development of cumulative knowledge in HRP [227], our aim is to establish these foundations for HDP to avoid repeating past mistakes and facilitate comprehensive understanding and development in this area. Alongside synthesizing relevant literature and transferring insights from other social psychological fields, this effort entails observing natural proxemic behaviors around drones and collecting empirical data through theoretically grounded user studies.

The Constraints of the Real-World However, progress in this area has been hindered by real-world constraints, including the limited drone design options available on the market, legal and practical complexities of conducting outdoor experiments, challenges in drone programmability, and safety concerns. These limitations significantly impede researchers' ability to conduct real-world experiments, often forcing them to deploy safety techniques, such as maintaining fixed minimum distances [5, 107, 164], using transparent walls [164], fixing the drone's position [107, 389], or using a fake one [82], that may compromise the ecological validity of their findings. To address these challenges, virtual reality (VR) has emerged as a promising solution for Human–Drone Interaction studies [382]. VR environments mitigate many of the real-world limitations and offer the potential to balance realism with experimental control, more accurately represent target populations, and reduce replication difficulties [31].

Unlocking Virtual Reality's Potential However, the effectiveness of VR relies on its ability to evoke natural reactions from participants. While its ecological validity has been demonstrated in some cases [278, 306], using VR for human–drone proxemic studies raises specific considerations that need to be addressed. Despite its vast potential, it is unclear **how to best use VR to study human–drone proxemics** (Research Question 2). In this context, it remains to be understood whether individuals exhibit natural behaviors while interacting with virtual drones and how the behavioral mechanisms under investigation might be altered. Beyond ecological validity, the success of VR also depends on practical considerations such as feasibility, the scope of what can be achieved, and the time and skills required compared to real-world studies. Through our work, we also aim to tackle these concerns and explore optimal approaches for utilizing VR in Human–Drone Proxemic studies.

In this thesis, we address the lack of theoretical foundation in the Human–Drone Proxemics field by proposing an initial theoretical framework grounded in social psychology and cognitive theories, supported by empirical findings. Additionally, this thesis explores the use of Virtual Reality as an innovative method to investigate Human–Drone Proxemics, offering guidelines and concrete implementation examples for its optimal use. This approach liberates researchers from the constraints of real-world studies and expands the scope of potential research avenues beyond current technological limitations.

1.2 Thesis Statement

RQ1: What motivates individuals' proxemic behaviors around drones and how do they manifest? In situations where humans and drones share the same space, people's distancing behaviors are shaped by various approach and avoidance motivations. These motivations—such as goal-oriented actions, protective instincts, communicative intentions, and arousal regulation—stem from how individuals perceive and interpret sensory information from the drone within their specific context. Multiple motivations can be at play simultaneously, with each exerting a different level of influence on the final proxemic outcome. When conflicting motivations arise (e.g., a desire to approach the drone while also wanting to maintain distance), individuals adapt by making physical, environmental, or cognitive adjustments. This could involve speeding up movement, altering their surroundings (like using noise-canceling headphones), or mentally filtering the drone's presence. These adjustments help people either reconcile conflicting motivations or reduce the importance of less critical ones.

RQ2: How best to use VR to study Human–Drone Proxemics? Virtual Reality impacts the proxemic process at multiple levels. Yet, considering the variables under investigation, ecological validity can be reached by controlling the participant's immersion level and the virtual setting. More precisely, by 1) identifying the relevant underlying mechanisms linked to the variables under investigation, 2) acknowledging the extent to which VR can alter these elements, and 3) limiting VR's impact through mitigation techniques. VR as a testbed for HDI proxemic experiments holds the potential to provide valuable insights about user's behaviour around drones while maintaining high levels of realism, replicability, safety, control and design possibilities compared to what is currently possible in real-world experiments.

1.3 Main Contributions and Research Questions

The Figure 1.1 illustrates the dynamic progression of this thesis, mapping the journey from initial research questions to the development of the main contributions and their interconnections.

As discussed in the introduction, proxemics presents a critical design challenge for autonomous drones. Inappropriate proxemic strategies can negatively impact individuals, causing discomfort or even potential physical harm, which could hinder the acceptance of drones and prevent society from reaping the numerous benefits their deployment could offer. Yet, there remains a significant lack of understanding regarding the underlying motivations driving individuals' proxemic behaviors around drones, complicating the rationale behind specific design decisions and the interpretation of observed behaviors in user studies. This need to understand people's spatial relationships with autonomous drones led to the formulation of Research Question 1: **What motivates individuals' proxemic behaviors around drones and how do they manifest?** The blue section of Figure 1.1 represents the journey focused on this question.

Following the formulation of RQ1, extensive literature reviews provided a deeper understanding of the research landscape and strategies to address the question (see chapter 2 "Literature Review"). It became evident that human–robot proxemic research had lacked a solid theoretical foundation, and the absence of a relevant model had impeded cumulative knowledge development [227]. Furthermore, drones emerged as a unique entity, perceived differently from ground robots, indicating that findings from human–robot interactions might not be directly applicable to drones [5, 107]. An initial exploratory study confirmed this and highlighted the potential role of multiple proxemic functions in HDI, contrasting with the prevalent emphasis on Hall's communicative proxemic function in other studies.

Given these insights, we determined that developing a theoretically motivated and empirically supported model of Human–Drone Proxemics would significantly benefit the field while addressing RQ1. As pointed out by Leichtmann et al. [227], different driving mechanisms can come into play when exhibiting proxemic behaviors around robots, and researchers should consider the most relevant ones in their studies. However, little is known about Human–Drone spatial relationships, making it difficult to motivate what might drive people's proxemics with drones. If proxemics is not the core aspect of their research, researchers may also not be experts on the matter and rely on theories used in previous works rather than delving into the broad proxemic research field to identify the most relevant models for their studies.

One significant contribution of our work is that we undertook this effort for the field. Drawing from social psychology, we identified four key driving mechanisms that individuals use to manage their spatial relationships and investigated how these mechanisms manifest and interact in Human–Drone interactions. As a result, RQ1 encompasses five sub-research questions: What is the role of the communicative (**RQ 1.1**), defensive (**RQ 1.2**), goal-oriented (**RQ 1.3**), and arousal regulation (**RQ 1.4**) proxemic functions in human–drone interactions? And finally how do multiple proxemic functions interact in HDI? (**RQ 1.5**). Given that each of these proxemic functions is associated with specific related work, theories, and considerations for HDI, we designed distinct user studies to explore each function in depth and understand their role in HDI. Chapter 4 dives into the role of the defensive proxemic function in HDI, chapter 3 addresses the communicative function, chapter 5 explores the goal-oriented function, and chapter 6 examines the arousal regulation function.

The synthesis of the findings from these studies, along with the identification of gaps in existing frameworks' ability to explain proxemic behaviors, contributed to the development of a comprehensive model of human proxemics with external entities (see chapter 7). While this model originates from human–drone interaction studies, it extends beyond drones to encompass a broader range of external entities. It integrates all relevant proxemic functions simultaneously, elaborating on how their interactions might shape proxemic outcomes. Recognizing that researchers lacked theoretical foundations for identifying driving mechanisms in Human–Drone Interaction (HDI) studies, our model fills this gap by offering a theoretically grounded and empirically supported framework. Researchers interested in examining the spatial influence of external entities can use this model to motivate, predict, and explain proxemic results, fostering hypothesis-driven experiments specific to their focus. Serving as a foundation, this model is designed to evolve and incorporate new empirical findings, contributing to the cumulative development of knowledge and ultimately leading to a more comprehensive understanding of Human–Drone Proxemics and proxemic behaviors more broadly.

All these studies were conducted in virtual or mixed reality environments to address the numerous challenges associated with real-world Human–Drone Proxemic studies. However, to ensure the validity of our findings, it was essential to understand the extent to which the behaviors observed and reported mirrored those that would have been obtained in a real-world experimental setting. This relates to our second research question (RQ2): **How best to use VR to study Human–Drone Proxemics?** Our approach to RQ2 began similarly to RQ1, involving an extensive literature review to understand the research space. This revealed that the impacts of VR have been extensively studied, enabling us to more appropriately predict how and what might alter virtual proxemic behaviors. To evaluate how a behavioral mechanism might be affected in VR, it must first be thoroughly understood. Consequently, as we progressed in addressing RQ1 and developing our understanding of proxemic behaviors, we concurrently addressed RQ2.

For each study and each proxemic function with its underlying mechanisms, we carefully considered how VR might alter observed behaviors and proposed techniques to mitigate these impacts, ultimately shaping the study designs. This dual approach led to a comprehensive understanding of how to use VR for Human–Drone Proxemic studies, offering theoretically and empirically supported guidelines for its application. While existing literature on VR often supported the validity of our studies, we also conducted real-world/VR comparisons to address specific concerns that the literature could not. Additionally, the use of VR entails more practical considerations. Having experimented with various implementation techniques, we aim to share these experiences to help researchers find inspiration on how to concretely and effectively use VR in their studies.

1.4 Thesis Walkthrough

The thesis has been structured as follows:

Chapter 2 *Literature Review* aims to provide the readers with a comprehensive overview of the research landscape in which this work resides and to offer all the necessary information to understand the rationale behind our chosen course of action. In addition, more targeted literature will be explored in subsequent chapters (3, 4, 5, 6, 7), focusing on specific behavioral mechanisms. The literature review begins by examining the field of Human–Drone interaction, with a particular emphasis on autonomous drones. Following this, we dive into the proxemic concept, offering a theoretical background that encompasses existing theories, the methodologies used in its study, and the associated limitations. Additionally, we provide an overview of proxemic research in Human–Drone interactions, pinpointing the primary gaps addressed in this thesis. Subsequently, we explore Virtual Reality, introducing its evolution, current capabilities, and core concepts before delving into its applications for human–drone proxemic studies. Finally, the literature review will conclude with a summary section, reiterating key concepts and identifying the gaps addressed in this thesis.

Chapter 3 *The Defensive Proxemic Function*, **Chapter 4** *The Communicative Proxemic Function*, **Chapter 5** *The Goal-Oriented Proxemic Function*, and **Chapter 6** *The Arousal Regulation Proxemic Function* each focus on a distinct proxemic function. In the introduction of each chapter, we outline the rationale and significance of examining the specific function, drawing on existing literature and insights from our user studies. The related works sections provide a targeted theoretical background, elaborating on relevant theories where applicable. Each chapter then presents the user study (see subsection 1.4.1 for an overview of the studies) conducted to assess and understand the impact of the specific proxemic function on Human–Drone interactions. The discussion sections address the implications for drone design, highlighting potential benefits and concerns, and consider how each function might interact with others, a topic further elaborated in chapter 7. Each of these chapters concludes with a comprehensive response to their corresponding sub-research question, from RQ1.1 to RQ1.4 and summarising contributions to RQ1.5 and RQ2.

Chapter 7 *A Unified Model of Proxemics: The Dynamics of Human Spatial Relationships with External Entities* introduces a unified model of proxemics that synthesizes existing frameworks of human spatial behavior, incorporating insights from our previous work to offer a comprehensive understanding of people's spatial relationships with external entities. Building on human–drone proxemic studies, the model integrates diverse proxemic motivations, highlighting their interactions, and offering new insights into the sensory processes underlying these behaviors. The chapter provides a detailed breakdown of the model's components, each illustrated by insights from user studies, enabling a direct connection to actual HDI observations. Additionally, we discuss the model's practical applications for both research and industry, with a particular focus on evaluating design choices in human–drone and human–robot interaction. Positioned at the early stages of a growing field, this work draws on lessons learned from human–robot proxemic research and lays the foundation for expanding our understanding of proxemic phenomena, extending beyond drones to include various interactive and autonomous systems.

Chapter 8 *Summary and Reflections on Thesis Research* offers a comprehensive summary of the thesis, illustrating how the various chapters are interconnected to address the research questions and detailing the resulting contributions.

Chapter 9 *Conclusion, Future Research and Final Remarks* discusses open research topics and promising directions for future studies in Human–Drone Proxemics and the application of VR in this research area. The chapter concludes the thesis with personal reflections from the author.

1.4.1 Overview of Studies

This thesis discusses 5 user studies.

Study #1: Exploratory Proxemic Behavior in Virtual Reality *(detailed in chapter 3)* This exploratory study involved 45 participants who navigated around a virtual drone under different height and framing (social vs technical) conditions. By using virtual reality (VR), we observed natural proxemic behaviors and recorded qualitative insights through 45-minute post-task interviews. Participants shared their experiences, discussed factors influencing their behavior, and provided feedback on the applicability of virtual encounters in real-world scenarios. It provided precious insights into the role the commonly used communicative proxemic framework and motivated our subsequent studies.

> **Publication Status** (Published) The findings from this study were initially presented as a Late-Breaking Work at the CHI 2022 conference [58], and later expanded into a full paper with detailed qualitative analysis, published in the International Journal of Social Robotics (IJSR) in 2024 [57].

Study #2: Defensive Proxemics in Real and Virtual Settings *(detailed in chapter 4)* This within-between design study involved 42 participants encountering drones approaching them at different speeds, either in a virtual environment or a real-world setting. The study investigated threat perception, discomfort, stress, and proxemic preferences, revealing defensive strategies individuals adopt when confronted by drones. The results highlighted parallels between virtual and real-world interactions, advancing our understanding of defensive proxemics in HDI and validity of VR proxemic studies.

Publication Status (Published) This study was presented at the INTERACT 2023 conference, where it won two awards: Best Paper by a Doctoral Student and the Reviewer's Choice Award [59].

Study #3: Exploring Social Proxemics with an Expressive Drone *(detailed in chapter 3)* This fully virtual study, involving 25 participants, explored the social use of space in HDI by integrating a digital face into a virtual drone. By manipulating the drone's emotional expressions and gaze behavior, the study assessed how these communicative social features impacted participants' perceptions and proxemic behaviors. Building on the insights from Study #1, this experiment deepened our understanding of the social use of space in HDI.

Publication Status (Published) This work has been published in the Transactions on Human–Robot Interaction (THRI) journal in 2025 [60].

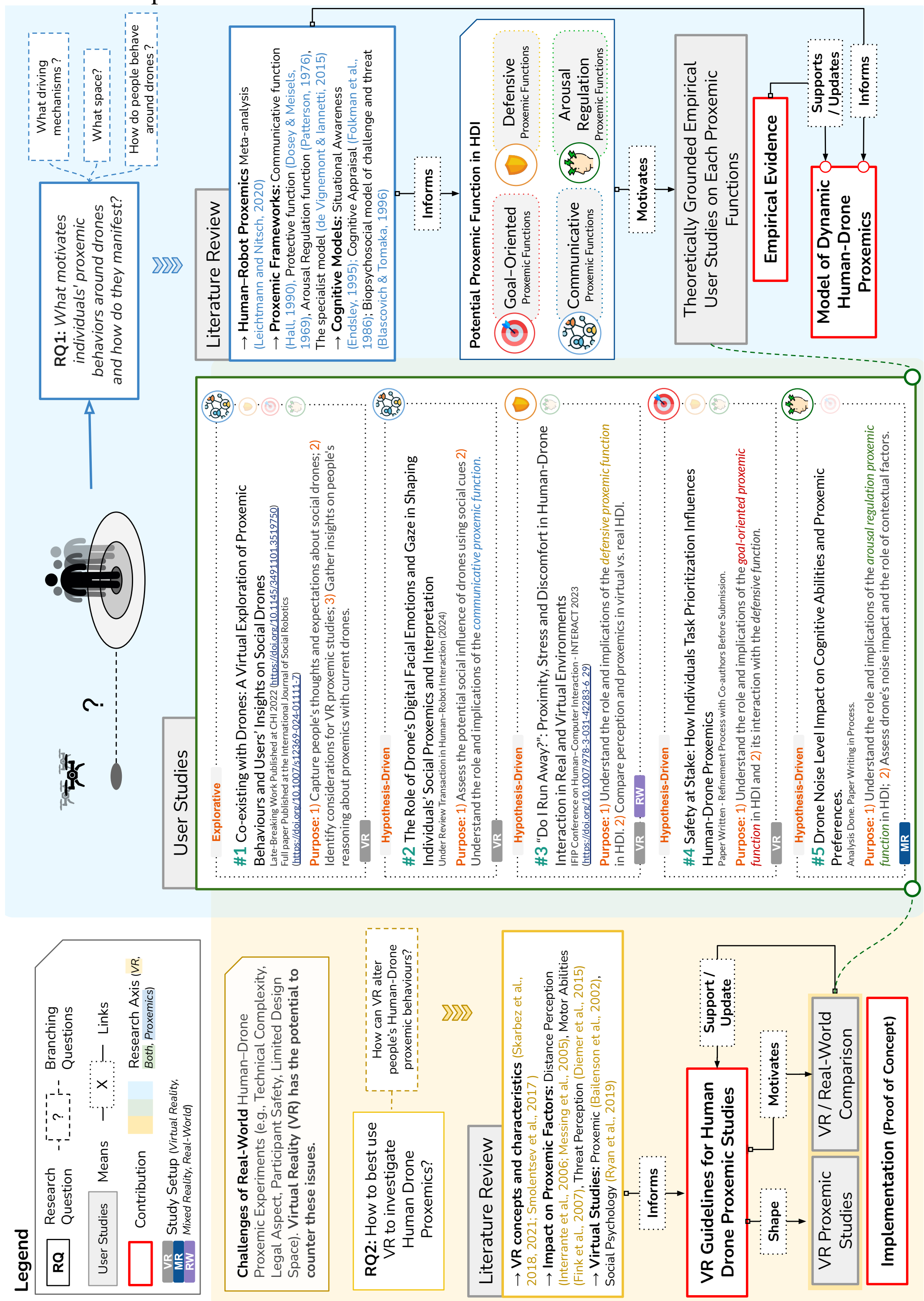
Study #4: Goal-Oriented Proxemics and Task Prioritization *(detailed in chapter 5)* This study, with 24 participants, investigated how task priority influences proxemic behavior when individuals perform a task alongside a moving drone. Participants experienced scenarios with varying levels of danger and task urgency (Relaxed vs. Competitive). Motivated by observations from Study #1, where some individuals prioritized task performance over discomfort, this experiment revealed how task demands interact with defensive behaviors in HDI.

Publication Status (Submitted) This work is complete and is currently under review at THRI.

Study #5: Arousal Regulation and Proxemics *(detailed in chapter 6)* This study focused on the arousal regulation function in HDI, involving 30 participants who experienced varying levels of drone sound and mental workload. The study sought to understand how drone noise and cognitive load influence people's proxemic behaviors and preferences, particularly in environments where individuals are already stimulated by other tasks. By examining how overstimulation affects distance regulation, this study offered new insights into sensory overload and arousal management in HDI.

Publication Status (In Preparation) This study is still in the process of being written up. It is currently reported in this thesis but has not yet been structured into a research paper for submission.

Figure 1.1: Dynamic progression of this thesis, mapping the journey from initial research questions to the development of the main contributions and their interconnections.



Chapter 2

Literature Review

This section provides an overview of the main related fields, aiming to equip readers with the necessary information to understand the research landscape of this work and to highlight the gaps that motivated our research questions and approach. We begin with an overview of the Human-Drone Interaction field, emphasizing Social Drones and the real-world challenges in this area. Next, we introduce the theoretical background of Proxemics, detailing its evolution, the main theories and methods used to study it, and their limitations. We then examine the literature on this topic from the perspectives of Social Psychology, Human-Robot Interaction (HRI), and Human-Drone Interaction (HDI). Following this, we focus on Virtual Reality, describing the technology, its hardware characteristics, and relevant concepts, and discussing its applications in research, particularly in proxemic studies, HRI, and HDI. Each section includes a summary to synthesize the most relevant information and highlight the research gaps addressed in this work. The Literature Review concludes with a synthesis section that consolidates the key points and underscores the contributions of our research.

2.1 Human—Drone Interaction & Social Drones Research

The term 'drone' is a catch-all phrase that encompasses various devices, including unmanned aircraft systems (UAS), uncrewed aerial vehicles (UAV), flying robots, quadcopters, and micro air vehicles (MAV). In this work, we define drones in a way that includes current terms and potential future variations. We use the following three criteria:

- **Unmanned:** No pilot inside, though it could carry people.
- **Flying:** Required but not exclusive; 'floating' may be more relevant, as seen with submarine drones. However, immersed devices impose a different interaction paradigm beyond the current scope of Human-Drone Interaction (HDI).
- **Artificial System:** Must be artificial but not necessarily material. For example, a flying companion represented in augmented reality is still considered a drone.

Like other technologies, the topic of drones transcends disciplinary boundaries. Researchers investigate drones from technical perspectives, focusing on developing new flying systems [80, 385], sensors, and video processing capabilities [29, 199]. As drones advance technologically, their applications expand from military to public use [173]. Sociologists study the integration and societal impact of drones, considering how social flying robots will fit into social relations and daily life [189, 320]. Psychologists and computer scientists, situated at the intersection of technology and human interaction, focus on "understanding, designing, and evaluating drone systems for use by or with human users and bystanders" [173, 349]. This line of research constitutes the Human-Drone Interaction (HDI) field.

2.1.1 Research Landscape

Drones can be categorized as a distinct subgroup within the broader class of robots, thereby falling under the Human-Robot Interaction (HRI) field. However, while HRI has traditionally focused on ground-based robots, flying robots introduce a novel interaction paradigm rich with new potential. Drones have unique attributes, such as their ability to fly, their striking appearance, and the sounds they produce. Additionally, they do not evoke the same associations in the popular imagination as traditional ground-based robots. Early research suggests that insights from HRI studies with ground-based robots do not seamlessly apply to Human-Drone Interaction (HDI) [5, 107]. This significant shift in the design space of HRI highlights the need to treat drones as a distinct entity, requiring fresh perspectives and approaches. This necessity ultimately led to the emergence of the Human-Drone Interaction (HDI) field.

The HDI field is recent yet rapidly expanding, with only two related publications in 2014, growing to 180 by 2018 [349], and about 1,970 today. This surge in research interest mirrors the increasing number of drone practitioners, as evidenced by an 8.5% rise in recreational registrations with the Federal Aviation Administration (FAA) between 2019 and 2020 [7].

Several literature reviews have been published, starting with Tezza and Andujar [349], which offers an overview of current drone models, innovations in interaction and communication techniques, prototypes, and use cases. While Tezza's review provides a valuable technical perspective on HDI (further developed in [228]), it places less emphasis on the human factor and autonomous drones. Addressing this gap, Baytas et al. [38] review studies on autonomous drones in inhabited environments, treating them as a distinct subject with unique design and human factor challenges. They specifically outline a framework of research avenues, identifying six Drone Design challenges and six Human-Centered challenges, with the proxemic dimension (explained in section 2.2) being one of them. Additionally, Baytas et al. define Social Drones as autonomous drones operating in inhabited environments, arguing that "since some form of social interaction is unavoidable when two or more living agents occupy the same environment, an autonomous embodied agent in an inhabited space can be similarly described as social" [38]. This perspective extends the notion of the social dimension to encompass various autonomous machines, irrespective of whether their primary function is predominantly social. Alternatively, drawing inspiration from the field of Social Robotics [54], another approach envisions Social Drones as entities designed to engage users on a deeper level, promoting well-being and facilitating interactions. These drones are equipped to *communicate* naturally through verbal and non-verbal cues, *comprehend* human behaviors to respond appropriately, and effectively *interact* with individuals to achieve their *objectives*. In summary, the former definition delineates when the social dimension becomes relevant, while the latter furnishes an aspirational description of the attributes social drones should aspire to embody. Together, these definitions delineate the research space of Social Drones. Its associated research axes, **Understand, Communicate, Interact, and Application**, are linked to specific research questions that often require multidisciplinary approaches to answer them. The following sections provide an overview of the HDI body of work on social drones within each axis.

2.1.2 Current Research

As previously mentioned, research on social drones can be categorized into four main axes aimed at understanding their impact on individuals (Understand), developing interaction techniques (Interaction), assess communication methods for drones (Communication), and explore concrete use cases (Application). These subdivisions offer a structured framework for organizing the body of work on social drones and help contextualize our contributions. However, it is important to note that individual topics can be approached from diverse perspectives. For example, sound can be studied under the 'Understanding' perspective to assess its effects on individuals [355], used as a communication channel for drones to convey their operational state [191, 239], explored as an interaction method (e.g., speech, whistle), and assess its suitability in concrete applications [276].

Moreover, these axes often intersect, and a single study may contribute to multiple areas. For instance, research on a specific interaction technique like 'handing over objects to a drone' [75] could simultaneously evaluate its effectiveness and its impact on individuals and associated considerations. Instead of solely focusing on the technique's development, researchers may prioritize understanding how these interactions affect people. That being said, the following sections provide an overview of the human-drone interaction body of work on social drones within each axis.

Understand This research axis focuses on exploring the impact of drones on individuals, their perception, the responses they elicit, and the significance of these responses.

Researchers have contributed to understanding people's perceptions of drones by uncovering privacy and safety concerns associated with drone deployment [82, 369], highlighting barriers to acceptance related to these issues [233, 356], and evaluating individuals' perceptions of privacy measures [387].

Additionally, researchers have explored how features of drone appearance affect people's perceptions and behaviors. Yeh et al. [389] examined how a "social design" compared to a default design influences people's perceptions and proxemic preferences. In a broader study, Wojciechowska et al. [381] investigated factors and characteristics influencing perceptions of flying robots based on their appearance, drawing on a significant database of existing models. Departing from typical multi-propeller drone appearances, Cauchard et al. [77] explored how radically different forms of drones might be perceived by people.

Beyond its' appearance, researchers started to assess how the sound it emits is perceived. An initial exploration of the psychoacoustic properties of drones' sound revealed a systematic perception difference compared to other road vehicles [85]. Later Gwak et al. [159] specifically explored the factors of the drone's sound factors influencing perceived annoyance. Finally, observing the apparent negative influence of drone's sound on users' experience, Wang et al. [370] explored techniques to mitigate its impact and assessed how would covering the drone's sound with natural sounds affect users' perception and proxemic preferences.

Another unique characteristic of drones is their ability to fly. Researchers have investigated how people perceive and respond to drones' flying behavior. Early studies by Duncan et al. [107] assessed comfortable approach distances for different flying heights, finding discrepancies compared to ground robots and humans. Acharya et al. [5] found different preferred distances between ground and flying robots. Further research has explored perceptions of flight factors and movements [42, 108], user preferences for approach modalities [235, 382], acknowledgment distances [192], and considerations for specific situations like body landing [27], handovers [75], and collisions [391].

Contextual factors have also been investigated, such as cultural differences [109], perception variations based on usage context [174], drone type (autonomous vs. piloted) [212], and location [371].

Communication In human-to-human interactions, verbal and non-verbal signals convey information to others, sometimes unintentionally. For example, an individual's facial expressions (social cue A) can accurately reflect their emotional state (information B), leading to social adaptation (response C). Investigating communication in the context of social drones involves exploring 1) How the spectrum of potential signals displayed by drones is perceived and interpreted (exploring B given A). 2) How to shape specific signals to convey desired information (exploring A given B). A third point, in relation with the *Understand* research axis entail investigating 3) The impact of conveyed information on people (exploring C given B and/or A). Researchers explore leveraging drones' flying capabilities to communicate messages through various movements, including intents [344], directional cues [88], acknowledgment behaviors [192, 259], and emotional expressions [79, 177, 322]. Additionally, light signals have been investigated to communicate directionality [345] and initiate communication interactions [149]. Some studies have focused on enhancing social interaction cues, such as implementing drone eyes [272] and developing digital facial expressions to convey specific emotional states [172].

Interaction Drones' capacities offer numerous applications opportunities. But it remains unclear how in practice will people interact with autonomous drones and make them perform specific tasks. Natural, intuitive and effortless interaction is often considered the objective to reach, but its complexities and the degree of ambiguity even for human–human interactions make it challenging to achieve for human–machine interactions. This research axis focuses on exploring interaction techniques with drones. Cauchard et al. [76] first explored how individuals would naturally interact with drones and found that gesture, voice, and multimodal interactions felt intuitive to participants. Gesture controls, both body and hand, have garnered significant interest, as seen in previous studies ([259], [260], [271], [286], [251], and [150]). Touch-based interactions have also been explored, with [4] and [236] contributing to this area. Other innovative interaction methods include using a smart ring for drone control [324] and a visual interface displayed on the ground by the drone, allowing users to interact through gestures [78].

Application While research continues to understand optimal drone design and interaction, the technology is already benefiting people through various applications. Different use cases bring specific considerations, prompting researchers to investigate human-drone interaction within these contexts [38]. For a detailed investigation of drone's application within the HDI reseach landscape, we invite readers to refer to the work of Herdel et al. [173] who provided a holistic view of domains and applications of use that are described, studied, and envisioned in the HDI body of work. Obaid et al. [270] also dived into specific considerations associated with domestic drones, exploring application areas, target users and interaction modalities.

A significant focus has been on emergency situations due to the high potential in this area. As of 2014, Camara et al. explored the idea of drone fleets to help rescuers operations over disaster scenarios [94]. Agrawal et al. [10] approached this topic by considering the human factor aspect of emergency situations, by designing an emercency system with semi-aunomous drones that centered around Situational Awareness (SA [115]). In firefighting, Khan et al. [206] highlighted the various benefits of drone deployment for both victims and firefighters during operations, while Alon et al. [18] introduced a user-centred design perspective for semi-autonomous drones in firefighting and Li et al. [229] presented a drone-based system for emergency operations with which firefghters can interact through sound, lights, and a graphical user interface. Fleck et al. [132] also explored the usability aspect of delivering lightweight defibrillators with drones.

Drones have been explored for various assistive functions, including guiding pedestrians [88, 211], ensuring their safety [207], and aiding visually impaired travelers [28, 295].

Early research in the field also focused on leisure applications, such as using drones as jogging partners [34, 262, 321]. This interest expanded to other activities, including meditation

[216], dance [120, 121, 378], and playful activities [22, 290].

Furthermore, the social potential of drones has led to exploring their role as companions [141, 200, 208] and sources of emotional support [124]. Gamboa [140] notably conducted an autoethnographic study documenting a year-long interaction between their family and a set of three land robots and one flying robot.

Lastly, drone applications in various industries have been explored, such as construction [16, 231] and warehouse management [293]. Other support applications include enhancing existing systems, such as providing haptic feedback in virtual experiences [3] and acting as remote eye-tracking sensors for public display interactions [205].

Synthesis This overview of the body of work on social drones illustrates the breadth of the field, its early development stage, and the significant research opportunities that remain. Within this research landscape and the framework outlined in this section, our work contributes to the Understand research axis. While the spatial relationship between drones and people could be leveraged as an interaction method [156] or means of communication, similar to human interactions, we assert that it first needs to be comprehensively understood. Most research on human-drone proxemics tends to overemphasize identifying influential factors, while the underlying mechanisms and meanings of these spatial adaptations remain misunderstood.

When we observe that a specific element of the drone's design affects proxemic behaviors, such as variations in preferred distances, the lack of understanding of the underlying mechanisms makes it difficult to contextualize this finding and assess its generalizability. This lack of insight diminishes the overall value of the observation, especially in Human-Drone Interaction (HDI), where previous research has shown that context significantly influences people's perceptions and behaviors. For instance, while privacy is often cited as a major concern regarding the deployment of social drones [82, 233], Herdel et al. [174] demonstrated that in severe situations such as earthquakes, individuals exhibit a more positive attitude towards drones and Khan et al. [206] found minimal privacy concerns among 911 callers when drones are used in emergency response scenarios.

A dedicated section of this literature review (see subsection 2.2.3) will further highlight the gaps we address within the Understand research axis, focusing on proxemics in Human-Drone Interaction (HDI). Additionally, our work aims to address the methodological limitations posed by the constraints of real-world user studies in this field, which are detailed in the following subsection.

2.1.3 Limits of Real-World User Studies

The HDI field employs a various set of methodologies found in other related fields such as Human–Computer Interaction, HRI or Social Psychology. Each of them aims to collect different insights and contribute to various aspect of this area of research. However, understanding human behavior typically requires observing natural interactions, often achieved through user studies. In these studies, experimenters observe people's behaviors as they interact naturally with drones while manipulating variables of interest. Unfortunately, this approach within Human-Drone Interaction faces significant real-world limitations, constraining the breadth of research possibilities and leaving large portions of the social drone design space unexplored. These constraints are detailed below, highlighting challenges that researchers encounter in conducting meaningful studies and advancing the field. One promising avenue to address these challenges is the utilization of Virtual Reality (VR) for studying human-drone interaction, as discussed in section 2.3.2.

Limited Design Options In conducting real-world user studies in Human-Drone Interaction (HDI), researchers can choose between using fake drones [82], custom-built drones, or commercial drones. However, the limited diversity of drone designs available on the market [381] significantly hampers the range of what can be studied. This range is further constrained by financial and programmability criteria. Consequently, HDI research often revolves around the dominant multipropeller design. A striking example is provided by Tezza et al. [349], who reported that 57% of the studies in their literature review used the same Parrot ARDrone. This has serious implications for the field, as it greatly limits the range of what can be investigated in the design spectrum of social drones, anchoring research around the dominant multi-propeller drone design. Illustrating this anchoring effect, Yamin et al. [386] leveraged deep learning-based techniques to generate novel, likable drone designs. However, they still relied on an image database of existing drones, which limited the outputs to designs similar to what already exists. Similarly, workshop designs with participants may perpetuate this anchoring effect. Participants might base their design decisions on their current vision of drones, proposing only slight variations of existing models, as observed in [200].

Legal Constraints Legal constraints significantly restrict the use of drones, especially those beyond a certain weight, making outdoor experiments legally challenging. This often necessitates the use of small, lightweight drones in indoor controlled environments, limiting the scope of potential studies and their applicability to real-world scenarios. Regulations around drone flights can vary widely by region, and obtaining necessary permissions for larger drones can be time-consuming and difficult, further limiting research opportunities.

Complexity Implementing complex interactions or behaviors with programmable drones is quite challenging and often requires advanced development skills. The practical complexities associated with hardware limitations (e.g., overheating, battery life) and environmental variability further exacerbate these challenges. As a result, conducting real-world human-drone interaction studies becomes highly demanding, hindering the exploration of more sophisticated and nuanced interactions.

Low Replicability Moreover, real-world environments introduce a high degree of variability that can complicate studies. Factors such as weather conditions, lighting, and unforeseen obstacles can affect the behavior of drones and the interaction experience. This variability makes it challenging to replicate studies and obtain consistent, reliable data. Whether researchers use a Wizard of Oz method with trained pilots or software with specifically programmed behaviors, the drone's behavior inevitably varies between participants within a single study and even more so between different studies. While this variability might be insignificant in some cases, studies specifically focusing on flying behaviors may suffer more from these real-world limitations.

Technological Feasibility Beyond financial, skill, or legal constraints, researchers are fundamentally limited by what is currently technologically feasible. This limitation makes it impossible to investigate a significant portion of the design space that is not yet attainable. For instance, while drone sound is often mentioned as a critical dimension to explore, it is challenging to control in real-world studies due to current technological constraints. The concept of silent or near-silent drones remains largely theoretical, as current propulsion technologies inherently generate noise. This limitation hinders research into how various drone sounds might affect users, and how quieter drones might integrate into noise-sensitive environments like hospitals or libraries, where reduced noise pollution could significantly enhance their utility and acceptance. Moreover, the exploration of drones with radically different forms or functionalities, such as drones capable of mimicking the flight patterns of birds or other animals, is beyond our present technological reach. Consequently, research is confined to existing models and technologies, preventing a comprehensive exploration of what future drones could be. These constraints not only limit the scope of current research but also impede our ability to foresee and prepare for future developments in HDI.

Safety Concerns Inherent to their current designs, drones can potentially harm individuals through collisions or contact with the propellers, resulting in cuts, bruises, or tangling in people's hair. While a growing body of literature has begun to examine human factors during human-drone collocated interactions, researchers often have to alter the realism of their experimental settings to ensure participants' safety. Techniques such as imposing a minimum distance [5, 107, 164], using transparent walls [164], fixing drone's position [107, 389], or fake drones [82] exist. Some researchers [107, 235] have pointed out the potential impact these safety measures might have on people's reactions near drones, questioning the ecological validity of their results.

2.1.4 Summary and Gaps

We highlight key points from the literature that have significantly influenced our research direction and are essential for understanding the value of our contributions.

- **Social Drones** are defined as autonomous drones operating in inhabited environment. While piloted drones are the extensions of their operators, autonomous drones are considered different entities, and when perceived by humans, trigger some kind of social influence raising specific design and human factor challenges that need to be addressed.

- **Proxemics** is a critical drone design concern for social drones identified by researchers that requires further investigation [38,349]. The next section 2.2 offers a detailed literature review on this concept and more accurately outlines how our contribution advances this area of research.

- **A Methodological Gap** exist in the HDI field, with researchers pointing out some critical limits of real-world user studies including safety concerns [107, 235], complexity, legal constraints, technological limitations, and poor design options [349], and emphasizing an urgent need for future work on prototyping and development tools for design researchers working with social drones [38]. One promising approach to address these challenges is the utilization of Virtual Reality (VR) for studying human-drone interaction. Despite the potential benefits of this method, as highlighted by Wojciechowska et al. [382], who rated it the second-best method for studying human-drone interaction after real-world collocated studies, VR remains underutilized in HDI research. It is rarely used and often not fully exploited; existing studies typically involve immersing participants in a virtual world where they can only observe a drone with an innovative design, without interaction [77], or sometimes without animation [200]. One potential reason for this is the lack of understanding of how VR can be effectively used in HDI. Our work aims to address this methodological gap by revealing the optimal use of VR for human-drone proxemics studies, providing researchers with guidelines and concrete practical examples for their investigations. Virtual Reality is further discussed in section 2.3.

The next section delves into the concept of proxemics, which pertains to human spatial behavior and the use of space. We will introduce existing theories and methodologies, review the progress made in Human-Drone Interaction research, and highlight the gaps our study aims to address. Our goal is to equip readers with the theoretical background needed to understand the gap identified in RQ1 and justify our course of action.

2.2 Proxemics

> Virtually everything that man is and does
> is associated with the experience of space
>
> Edward T Hall, *The Hidden Dimension*

The notion of space is intriguing, taking on diverse forms and serving various functions.

Spaces can be fixed and sharply defined, like national borders and their inner territories, or they can be moving, abstract and diffuse, resembling the social and personal zones we navigate daily. Individually, the space around each person carries personal significance and relevance. Take a moment to look around you. If you're at your desk, try estimating which objects you could easily grasp from your seat, and observe how accurate your estimations are, experiencing the intuitive perception of personal space. In social contexts, experiment by moving a step or two closer to someone you're conversing comfortably with. Notice how this simple act alters the interaction dynamics, possibly eliciting slight discomfort or an urge to step back in yourself, or prompting your conversational partner to subtly adjust their position. These everyday experiences underscore our innate sensitivity to spatial relationships, shaping how we interact with our environment and others, and the subtle messages conveyed through our use of space. The study of these phenomena and theories concerning human use of space is known as 'Proxemics'.

2.2.1 Evolution of the Concept and Theories

Hall's Framework – *Communicative Function*

This subconscious and dynamic process of regulating distances with entities in our surroundings is termed Proxemics, a concept introduced by Edward Twitchell Hall and eloquently described as "The Hidden Dimension" of human social interactions [163]. As an anthropologist, Edward T. Hall offered a social perspective on spatial dynamics, viewing the distancing behavior among humans as a culturally nuanced phenomenon and a form of communication. An essential aspect of Hall's proxemic theory is its emphasis on the primary role of the mostly unconscious perception and interpretation of sensory inputs (e.g., olfactory, touch, vision) in the formation of proxemic behaviors, highlighting its inherent physiological foundation. This sensory perception and the meaning associated with perceived cues (e.g., physical contact, eye contact) can significantly differ between individuals and in various contexts, explaining the variability of observed proxemics in social settings across cultures. Hall identified four proxemic zones, each with close and far phases, reflecting varying degrees of closeness and relational intent. These zones provide insight into the types of activities and sensory inputs experienced within them:

1. Intimate Space (0-45cm): Reserved for close personal interactions.

2. Personal Space (30-120cm): Used for interactions among friends and family.

3. Social Space (120-365cm): Suitable for acquaintances and casual conversations.

4. Public Space (365cm and beyond): Appropriate for public speaking or interactions with strangers.

Additionally, a key aspect of Hall's theory, often overlooked, is the dynamic nature of space. While his framework introduces labeled proxemic spaces, it is important not to view space as a fixed dimension. Rather, human perception of space is closely tied to actions and interactions within an ever-changing environment.

Ultimately, when justifying its framework, Hall synthesised that "the scientist has a basic need for a classification system, one that is as consistent as possible with the phenomena under observation and one which will hold up long enough to be useful. Behind every classification system lies a theory or hypothesis about the nature of the data and their basic patterns of organization. The hypothesis behind the proxemic classification system is this: it is in the nature of animals, including man, to exhibit behavior which we call territoriality. In so doing, they use the senses to distinguish between one space or distance and another. The specific distance chosen depends on the transaction; the relationship of the interacting individuals, how they feel, and what they are doing."

Limitations Hall's framework stands as one of the most significant contributions to the field of proxemics and is a fascinating read. Its influence exceeded its research field and found applications in many others, including Architecture [279], Human–Computer Interaction [156] and Human–Robot Interaction [263]. However, it is limited by its initial focus. Hall, as an anthropologist, concentrated on understanding how humans use space within societies from a social perspective. This focus does not encompass the full range of proxemics, such as the use of space for other, less social functions or interactions with non-human entities. These unexplored aspects might involve different proxemic systems and be driven by distinct driving mechanisms [167]. As Hall himself pointed out, "Any attempt to observe, record, and analyze proxemic systems must take into account the behavioral systems on which they are based." Heini P. Hediger, the animal psychologist whose work inspired Hall's model, highlighted a clear distinction between the mechanisms driving territoriality and appropriate spacing among animals (including humans) of different species and those within the same species [170] with only the later making social use of space.

With these initial insights into proxemics, we wonder: Are autonomous drones perceived in society more akin to humans or as entities of another species? Are proxemic behaviour with Drones socially-driven? We will leave these questions pending for now, but invite readers to reflect on their implications for understanding human-drone proxemics. While Hall's framework is extensively used in Human–Robot and Human–Drone proxemics, one might challenge its relevance or at least consider the other potential theories presented below.

Complementary Proxemic Theories

While Hall's proxemic framework is certainly the most developed theory of human spatial behaviors, other theories have been proposed. These alternative models, rather than contradicting Hall's framework, contribute to a comprehensive understanding of what drives people's proxemics. This can be illustrated by Hediger's observation that "each animal is surrounded by a series of bubbles or irregularly shaped balloons that serve to maintain proper spacing between individuals" [170]. Although this metaphor can be somewhat misleading, since actual bubbles do not accurately reflect proxemic phenomena, such as the gradations of resistance to intrusion [167], the concept is useful for understanding that multiple spaces around us are active with various purposes. Each "bubble" corresponds to a specific behavioral mechanism and serves a specific function. In his review of Human Spatial Behavior, John R. Aiello [11] summarizes some of these alternative theoretical frameworks described below.

Equilibrium Model – *Communicative Function* In line with the idea of multiple active forces driving proxemics, Argyle and Dean introduced the **intimacy equilibrium model**. They drew inspiration from Miller's theory [258], which posits that approach and avoidance forces drive organisms to a stable equilibrium point where these opposing forces are balanced [11, 24]. Applied to intimacy regulation, Argyle and Dean suggest that human interactions are governed by balancing communicative behaviors—such as physical distance, eye contact, smiling, and the intimacy of the topic—to reflect actual levels of intimacy between interactants [24]. Similar to Hall's framework, the intimacy equilibrium model describes a social and communicative function of proxemics and thus falls short in explaining non-socially driven behaviors. Nonetheless, its emphasis on the role of social cues in proxemics makes the intimacy equilibrium model a popular and relevant framework in studies exploring these aspects, such as investigating the impact of avatars' gaze on proxemics in virtual reality [46] or exploring how it transfers to humanoid ground robots [263].

Over time, the foundational theory of approach/avoidance motivations that Argyle and Dean relied upon has been further developed to encompass multiple neuropsychological systems and their complex interactions [89]. Interestingly, while approach behaviors are typically associated with positive affective states and stimuli, Harmon-Jones et al. [165] provide evidence that approach motivation can also be evoked by negative stimuli and experienced as a negative state (e.g., attack defensive behaviors). Furthermore, they argue that external stimuli are unnecessary to evoke approach motivation. This theory further underscores the instinctive nature of proxemics and offers valuable high-level insights for developing a relevant model that explains human–drone proxemics, providing cues addressing interactions of multiple active proxemic functions. However, it remains too abstract for explaining human–drone proxemics at a practical level useful for researchers and designers. It falls short in explaining concrete observations and isolating specific motivations, which are crucial for developing design rationales and motivating specific investigations in human–drone interactions.

Expectancy Theory – *Mixed Functions* Burgoon and Jones [67, 68] developed the expectancy-violation theory of personal space, proposing that expected interaction distances stem from both situational norms and the characteristics of the interacting individuals. Instead of describing a specific use of space, they offer a list of "propositions" to explain proxemic dynamics. Driven by social norms and individual characteristics, people project an expected appropriate distance when interacting with one or multiple agents. Small deviations from this expected distance may go unnoticed, whereas large deviations (either too close or too far) are likely to produce negative effects. The effects of modest deviations can be either positive or negative, depending on the reward value attributed to interacting with the other person. They also describe a threat threshold, below which another's presence instills a sense of discomfort and potential threat. Although somewhat limited in explaining the full diversity of human spatial behavior [11,167], this model introduces important factors related to people's expectations and previous experiences. It could be integrated into broader models, such as the arousal model presented below.

Arousal Model – *Arousal Regulation Function* Another proposition to explain human spatial behaviors is the Arousal Regulation model. Patterson [282] proposed that all interactions involve arousal, and variations in interpersonal distances can trigger physiological responses categorized as either positive or negative. When arousal reaches a sufficient intensity, it prompts behavioral adjustments: approach behaviors in response to positive arousal and withdrawal behaviors in response to negative arousal.

Thus far, the proposed theories originate from the fields of social psychology and anthropology, focusing primarily on the social aspects of human behavior and the interpersonal distance people maintain with others. However, examining the use of space from an environmental perspective could be equally informative in understanding human proxemics around drones. Extending the model to other sources of arousal, Evans [122] suggested that maintaining specific distances regulates the amount of sensory input, ensuring it remains below an acceptable threshold to prevent sensory overload. In an open-plan office, employees might adjust their desks or seating arrangements to manage sensory input from their surroundings. Moving a desk away from a noisy corridor or closer to a window with a pleasant view helps regulate arousal levels, contributing to better focus and comfort.

The Arousal Regulation model is valuable as it encompasses non-social factors that may drive behaviors involving both human and non-human entities. For instance, considering that drones can potentially be perceived as threats [82] or produce annoying sounds [159], inducing arousal in users or bystanders, it is reasonable to expect that the arousal regulation function could influence people's proxemics around drones. Despite its potential relevance, this proxemic model and its associated behavioural mechanisms [48], haven't yet been considered for Human–Drone Interactions.

Safety Margin – *Defensive Function* Other researchers have proposed a primary protective function of proxemics. Dosey and Meisels , as well as Sommer, described personal space as a "buffer zone" that serves as protection against perceived emotional, physical, or privacy-related threats [11,103,336]. It echoes Hediger's "Flight Distance", which describe a defensive function of space, triggering withdrawal behaviour when an enemy is deemed too close [170]. When walking alone at night, a person might keep a greater distance from others, especially strangers, as a defensive measure. If someone approaches too closely, this might trigger a withdrawal behavior such as crossing the street or quickening their pace to create a safety margin and reduce perceived threats. Similarly, the concept of peripersonal space (PPS; defined as the reaching space around the body) is associated with a "safety margin" [309]. Peripersonal space is highly flexible [243] and its representation relies on individual-specific integration of salient sensory inputs in a given situation. Factors such as the orientation of threatening objects [86], their approach [65, 360], acute stress [113], and personality traits (e.g., anxiety [309, 337]) influence PPS. Dosey also predicted that greater spatial distances will be used under stress conditions, by highly anxious people, and by people who perceive their body-image boundaries as weak or unstructured, in line with the findings from the PPS studies [103]. Behavioural mechanisms related to defensive behaviors and stressful encounters describe the detection, proximity, and intensity of a perceived threat as triggers for specific behaviors (e.g., Risk Assessment [44, 45] and Cognitive Appraisal [48, 133]). The defensive proxemic function is notably linked to the arousal regulation function presented above, with the key distinction being that threat detection induces arousal, whereas arousal may be induced by other non-threatening sources. Again, considering drones are often perceived as threatening entities [82], it appears relevant to expect that individuals proxemic behaviour during a drone's encounter might be driven by defensive mechanisms although it hasn't been explored yet.

An Action Space – *Goal-Oriented Function* When navigating the space around us, our movements are often driven by conscious or subconscious goals, which in turn shape our proxemic behaviors. In a busy airport, travelers navigate through the space with specific goals, such as reaching their boarding gate or picking up luggage. They may move quickly through crowds, making calculated decisions about when to weave through people or wait for an opening to achieve their objectives efficiently. If someone needs assistance, they might approach information desks or personnel, altering their proxemic behavior based on their immediate goal. This concept aligns with the approach/avoidance motivation system, which suggests that movements are driven by the potential for rewards and punishments [89]. As Hall noted, human "perception of space is dynamic because it is related to action—what can be done in a given space" [163]. De Vignemont et al. [96] further emphasize the duality of peripersonal space, distinguishing between defensive space, which serves as a protective buffer, and working space, within which actions are possible and effectively executed. This distinction highlights that proxemic behavior is not solely about maintaining safety but also about facilitating goal-oriented actions. While this environmental perspective on the use of space for executing specific actions has not been as thoroughly theorized or received as much attention as the theories presented above, it is a crucial aspect to consider. Practically, if autonomous entities like drones are deployed, they will navigate and potentially approach busy individuals carrying out their daily tasks. These individuals may also approach drones with specific objectives in mind.

Summary & Key Insights

In 1966, Edward T. Hall posed the question, "How many distances do human beings have and how do we distinguish them?" [163]. Nearly 50 years later, De Vignemont et al. echoed this inquiry with, "How many peripersonal spaces?" [96], highlighting the ongoing quest to understand human spatial behavior. While the complexities of this hidden dimension persist, the foundational works discussed earlier provide valuable insights relevant to our research questions RQ1 "*What motivates people's proxemic behaviors around drones, and how do they manifest?*" and RQ2 "*How to best use VR to investigate human–drone proxemics?*" Key insights include:

1. **Perceiving and interpreting sensory inputs** forms the initial stage of the proxemic process. This is crucial when considering the use of virtual reality to study proxemic behaviors, given the potential alteration of sensory experiences.

2. **Proxemic behaviors are mostly unconscious**, as emphasized by Hall, who noted that they "have to be investigated without resort to probing the subjects' mind" [162]. This fundamental characteristic of proxemics guided the methodologies chosen for our own investigations and prompted considerations about the suitability of commonly used methodologies, as outlined in the following section.

3. **Space serves multiple functions** associated with specific behavioral mechanisms, including communicative (social meaning) [24,163], defensive (threat mitigation) [96,103,336], arousal regulation (maintaining acceptable arousal levels) [122, 282], and goal-oriented (executing actions) [89, 96, 163] functions. While Leichtmann and Nitsch encourage researchers in human-robot proxemics to apply relevant frameworks [227], the nascent field of Human-Drone Interaction lacks sufficient understanding to definitively prioritize one function over another. Drawing insights from human-human interactions, it may even be advantageous to consider all proxemic functions when studying human-drone interactions, as each could be simultaneously active. However, to substantiate their relevance and understand how they apply to the novel human-drone interaction paradigm and associated design implications, empirical assessments are crucial. We need to explore how each proxemic function specifically applies to interactions involving drones.

4. **Individual characteristics and contextual factors** can significantly influence the proxemic process and its outcomes (e.g., personality, previous experiences, spatial arrangement), resulting in varied behaviors across different settings and populations [103, 163].

This expands the scope of considerations for proxemic factors in human–drone interactions beyond the design of drones themselves.

5. **Approach and avoidance forces** drive individuals toward a point of equilibrium [24, 89], aiding in understanding how various proxemic functions collectively contribute to a unified proxemic outcome.

6. **Proxemic behaviors are dynamic**, involving continuous and mostly unconscious adjustments within ever-changing environments. This directs our research focus towards understanding the dynamic nature of proxemics in human-drone interactions, capturing not only the present state (instant t) but also its evolution over time (t+1).

While these insights are informative and have received empirical support for human interactions, their application to human-drone proxemics remains hypothetical, underscoring the need for empirical investigations. In particular, "any attempt to observe, record, and analyze proxemic systems must take into account the behavioral systems on which they are based" [163]. Therefore, to build a comprehensive understanding of human-drone proxemics, each of the previously introduced proxemic functions must be considered from a human-drone interaction perspective. Targeting each of them separately would enable us to better understand their individual roles in people's proxemics, their underlying associated mechanisms, and the specific implications for social drone design. Now the question arises as to how investigate proxemics. The next section provides an overview of existing methods and highlights a current methodological gap we aim to address using virtual reality.

2.2.2 Existing Research Methods & Limits

Various methods exist to investigate proxemics, each with its own limitations and varying levels of control and realism, as discussed in previous reviews [11, 167, 227]. These methods are summarized below:

- **Projection**: In this method, subjects are asked to imagine a specific situation and project their likely behavior within that context. Participants typically manipulate dolls, figures, or place markers to indicate where they would position themselves spatially. However, this technique has faced significant criticism due to its low correlation with real-life measures, inconsistent findings, and widely fluctuating effect sizes. As Hayduk noted, "Although [...] these measures do measure something, that something is not personal space" [167]. Aiello [11]reached a similar conclusion in his review of human spatial behavior studies. Although rarely used today, this method accounted for approximately 40% of proxemic investigations at the time of Aiello's review. Nonetheless, the ease of administration of this technique makes it an attractive approach. While it may not be useful to investigate individual's spacial behaviours, it could be used to gather insights about how people think of themselves in relation to others [11] and their "perceived" personal space [148].

- **Quasi-projective / Simulation**: In this method, subjects use their own bodies to distance themselves from another real (e.g., experimenter, confederate) or imagined (e.g., mannequin) agent in a laboratory setting, simulating a real interaction. The most common simulation technique is the stop-distance procedure, where subjects either approach or are approached by another person and must stop the approach at the point where they start feeling discomfort or consider it ideal for interaction. Different angles can be considered [169, 382], but interactants usually face each other [374]. This method offers significant control over experimental variables and enhances realism compared to projection methods.

  However, a notable concern with this approach is the potential artificial emphasis placed on spatial dimensions by prompting participants to consciously "stop" their approach. As Hall noted [162], "proxemic patterns are primarily maintained outside of conscious awareness and thus should be studied without delving into the subjects' minds". The stop-distance protocol inevitably alters this unconscious process.

  The validity of these simulation techniques for studying human spatial behaviors remains a subject of ongoing debate. On one hand, measures obtained through this approach simulate interpersonal interactions by integrating proprioceptive cues akin to those experienced in real-life situations. On the other hand, these measures often demonstrate weak correlations with actual interpersonal distances observed in real-world interactions [11]. Notably, participants fail to replicate distances maintained during natural interactions when using the stop-distance method [329]. Therefore, Aiello advises caution in generalizing findings derived from quasi-projective measures, suggesting that further validation using naturalistic methods is warranted. Additionally, Hayduk [168] argues that measures obtained with the stop-approach procedure represent "momentary spatial preferences" in a dynamic proxemic process that is continually open to modification. This aligns with the sixth key insight from the literature on human proxemics, emphasizing the ever-changing nature of proxemic behavior.

- **Interactional or Field / Naturalistic**: This approach entails directly observing people's behavior during interactions, either in naturalistic settings or a laboratory environment [11]. The latter offers several advantages, combining the high control of previous methods with the ability to observe natural proxemic behaviors since participants are unaware that their spatial behavior is being scrutinized. Although laboratory settings may present risks of limited generalizability, these are often outweighed by the benefits of control compared to the unpredictability of natural environments. Edward T. Hall [163], a leading figure in this naturalistic approach, developed his framework directly from observations of individuals' actual use of space.The ideal setting for a proxemic study to obtain generalizable results involves observing human behaviors as identifiable individuals interact in their natural environment, unaware that their spatial behavior is being scrutinized. However, such settings are difficult to control, replicate, and measure proxemic behavior accurately [359]. Considering these criteria, an emerging technique shows promise: immersive virtual environments [32, 183]. This method allows for the creation of highly controllable yet realistic settings and enables accurate proxemics measurements without the subject's awareness.

- **Immersive Virtual Environment**: In 2002, Blascovich et al [47, 241] published a paper highlighting the considerable potential of immersive virtual environment technology as a methodological tool for social psychology, citing early promising results. Authors said that this technology had the potential to eliminate the trade-off between mundane realism and experimental control, target a more representative population, and reduce the difficulty of replicating studies [47]. Early research by Baileson and colleagues showcased the social influence that virtual human representations can wield within VR, successfully replicating proxemic findings from Argyle's equilibrium model [46]. They employed an interactional approach, which, as described earlier, enables the observation of natural proxemic behaviors. These behaviors were accurately measured over time using headset tracking, thereby demonstrating VR's potential for studying human spatial behaviors. Using a similar approach, Dotsch and Wigboldus [104] showed that native Dutch participants maintained more distance and showed an increase in skin conductance level when approaching Moroccan avatars as opposed to White avatars while being immersed in a virtual environment. This technology has since been used extensively to study human spatial behaviors [86, 145, 182, 183, 185, 298, 300, 305] and has gained increasing interest over the years due to significant technological advancements, which have expanded its possibilities. Additionally, there is now a better understanding of mitigation techniques to address potential alterations in observed behaviors. While true-to-life digital simulations of grounded reality have many practical applications, researchers can also manipulate variables to create or measure effects that would not ordinarily occur in grounded reality, such as accurately controlled amounts of mimicry between interactants [30]

Ultimately, various techniques exist to study proxemics, each with its strengths and weaknesses. Importantly, since the use of space is mostly unconscious, methods where participants exhibit proxemic behaviors without being aware they are being observed are considered preferable (Interactional or Field / Naturalistic Methods). Such techniques may offer less control or accuracy in measurements, but the emergence of virtual reality and its successful applications in the field show promise for easier access to interactional methods that maintain high control and realism. VR also expands the possibilities to settings that would be difficult to replicate in the real world [306]. With this understanding of proxemic theories and the methods used in the field, let's examine the research in human–robot and human–drone proxemics.

2.2.3 Humans–Robot & Human–Drone Proxemics

> Science is built up of facts, as a house is built of stones; but an accumulation of facts is no more a science than a heap of stones is a house.
>
> Henri Poincaré, *Science and Hypothesis*

Our work focuses on human-drone proxemics, specifically uncovering what drives people's use of space during human-drone interactions. As highlighted in the review of social drone research, these flying machines are considered distinct from ground robots due to their unique characteristics, an assumption supported by early studies reporting perception and behavioral differences [5]. While findings from human-robot proxemic research may not be directly transferable to drones, we nevertheless examined the existing research and its development to find inspiration for how human-drone proxemics could evolve. In this subsection, we will first provide an overview of the research conducted on people's use of space during human-drone interactions (HDI). We will then highlight the various limitations and issues currently present in the field, notably the lack of relevant theoretical foundation and methodological constraints.

Overview

To date, researchers have explored various aspects of human-drone interaction (HDI) related to proxemics, consistently using the stop-approach procedure or slight variations of it, with only one study using an interactional method [109]. Researchers have investigated how drones should **approach** people. Jensen et al. [192] examined drone gestures for communicating acknowledgments and used the stop-approach procedure to determine the preferred interaction distance. Wojciechowska et al. [382] used a similar method where participants observed a drone approaching them multiple times under varying conditions of speed, direction, trajectory, and stopping distance to identify their preferences. Factors impacting this preferred stop distance have also been investigated. Duncan and Murphy [107] used the stop–approach procedure to investigate the impact of different **flying heights** of the drone on proxemics preferences. While they did not find significant impact, the experimental setup with the drone being fixed to a moving rail was considered potential invalid. Yeh et al. [389], investigated how a **social aspect** for the drone might impact proxemics and using a stop approach procedure social shaped design with decreased the acceptable distance markedly. E et al. [109], in a study that explored **cultural difference** in HDI during which subjects naturally interacted with a drone (interactional method), found that Chinese participants exhibited closer interactions with the drone compared to American participants. Lieser et al. [235] using the stop–approach procedure tried different **approach directions** and verified whether participants would let the drone enter reaching space to enable physical interaction, showing that it appears feasible. Wang et al. [370] explored how covering the drone's noise with **natural sounds** could alter participants perception and its potential interaction effect with the drone's position, showing that natural sounds had a substantial positive effect only at the farthest distance. Researchers have also investigated how HDI **differs from ground robot** interaction, demonstrating increased stress and distance preferences with drones [5]. Additionally, **interaction methods** that rely on close proximity have been explored, including body landing [27], touch interactions [4, 236], natural interactions [76, 109], and hand-over methods [75].

Lack of Relevant Theoretical Foundation

In Human–Robot Proxemic Research In a recent meta-analysis of research on human-robot proxemics, Leichtmann and Nitsch [227] reviewed the numerous influential factors explored over the years in HRI, such as human-related (e.g., gender, age, personality), robot-related, environmental, approach-related, and other factors. They concluded that the overall results were quite mixed and inconsistent. They specifically highlighted the lack of a relevant theoretical foundation (with a few exceptions [263]) and the inadequate consideration for contextual factors as potential causes for these inconsistencies. More importantly, they pointed out the absence of cumulative knowledge development over the years. Poincaré aptly illustrated this issue in 1902 [289], writing that "science is built up of facts, as a house is built of stones; but an accumulation of facts is no more a science than a heap of stones is a house". Interestingly, Hayduk [167] reached the same conclusion in his 1983 review of personal space research, stating that "we need to switch our focus from discovering the determinants and consequences of particular spacing preferences to the processes providing the links between already specified causes and consequences", illustrating this long-standing issue. Both assessments suggest a shift is needed in proxemic research from merely identifying influential factors to understanding the underlying mechanisms that make them influential. It is one thing to find that someone's height influences proxemic preferences, but understanding why is a different and more complex challenge.

Leichtmann and Nitsch [227] also criticized the over-reliance on Hall's framework, noting, "While one would expect distances comparable to those in human-human distancing situations for human-like robots according to the anthropomorphization literature, the distance is more unclear for mechanical-looking robots. Mechanical-looking robots might not be perceived as social beings but rather as simple technical equipment. Distances are thus shorter because social norms do not hold". This observation is particularly relevant for human-drone proxemics due to drones' mechanical design. Leichtmann and Nitsch [226] further emphasized the need to consider these contextual factors in human-robot proxemics research and urged researchers to explore this aspect more thoroughly.

In Human–Drone Proxemic Research While the field of human-drone interaction is still in its infancy, it is evident that the research so far follows the same inefficient path criticized by Leichtmann and Hayduk—focusing on identifying influential factors rather than understanding why they are influential. Some valuable research efforts have been made to understand the distinct nature of drones and motivate the development of a novel human-drone proxemic field [5, 107]. However, much of the existing research either lacks theoretically grounded motivations [235, 389] or relies on Hall's framework to discuss results, often limiting discussions to where participants' proxemic preferences fit within Hall's proxemic zones [192, 382]. Using Hall's framework is relevant if assuming that drones are being treated as social actors in a manner similar to humans, and that people's proxemics reflect some kind of intimacy levels between the two interactants. Yet this assumption may not always be valid, especially given the very mechanical aspect of current drones. This approach provides very little understanding of the mechanisms driving these results and limits their generalizability, given that proxemic behaviors [163] and perceptions of drones [82, 174] can significantly vary in different contexts. Instead, researchers often justify their work and methodology by relying on previous empirical studies, repeating the same mistakes.

Current research on human-drone proxemics primarily focuses on proximate explanations, describing the determinants and causes of the phenomenon. As Hayduk and Leichtmann suggest, we believe the field needs to shift towards proposing ultimate explanations—explaining why these observations occur in the first place. This approach would enable empirical findings to achieve their maximum potential research value by setting expectations using relevant theoretical frameworks, and determining whether new empirical findings are confirmatory and integrate well with existing research, or are surprising and require further replication and scrutiny [264]. This shift would facilitate the development of cumulative knowledge in human-drone proxemics, transforming a "pile of rocks" into a cohesive "house."

This perspective motivated our approach to answering RQ1. While Leichtmann and Nitsch advise researchers studying human-robot proxemics to consider the most relevant proxemic framework for their studies, little is known about human-drone spatial relationships, making it challenging to determine what might drive people's proxemics with drones. If proxemics is not the core aspect of their research, researchers may not be experts on the matter and may rely on theories used in previous works rather than delving into the broad proxemic research field to identify the most relevant models for their studies. Therefore, we decided to explore each of the potential proxemic functions previously outlined in the literature on human spatial behavior, theoretically and empirically investigating how they apply to human-drone proxemics. This approach aims to uncover their roles, specific implications, and associated behavioral mechanisms.

Recognizing the limitations of a fragmented approach, we aim to integrate various proxemic functions into a unified theoretical model of human spatial behavior with external entities, encompassing human–drone proxemics. By addressing the lack of a cohesive theoretical foundation and rationale for identifying key driving mechanisms of spatial behaviors in HDI studies, our model offers a valuable, theoretically grounded, and empirically supported framework (see chapter 7). Researchers can leverage this model to motivate, predict, and explain proxemic outcomes in relation to specific focuses, fostering hypothesis-driven experimentation. Designed as a foundational framework, the model is intended to evolve, incorporating new empirical findings over time.

Methodological Limitations

Exploring human spatial behaviors around drones necessitates enabling some form of spatial proximity between the two, ideally through a natural process (as in [109]). However, drones' flying capabilities often depend on rotating propellers, which can cause serious harm if they come into contact with people. This places Human-Drone Interaction (HDI) within the "Dangerous HRI" area of Human-Robot Interaction research [301]. This methodological requirement and safety issue make conducting real-world proxemic studies challenging for researchers.

Interactional methods have only been utilized once to investigate people's proxemic behaviors [109], maybe due to the challenge of controlling participants who might endanger themselves by approaching the drone too closely. Consequently, researchers rely on the stop-approach procedure, which provides greater control. Nonetheless, this approach tends to overemphasize a single distance measurement to gauge personal space and proxemic behaviors. However, as previously mentioned, proxemics literature underscores that personal space is a dynamic continuum, reflecting adjustments made in ever-changing environments, and can significantly vary based on situational and internal factors. This misleading and inaccurate conception of personal space as a clear boundary around individuals has also been identified as a problem in human-robot proxemic research [227].

Moreover, even if the stop–approach procedure gives more control over participants behaviour, experimenters must employ various additional safety techniques, such as transparent safety walls [164], securing the drone with cables [389] or other methods [107], using fake drones [82], or artificially setting minimum safety distances from the drone [5, 107, 164]. Most of these techniques are clearly visible to participants. Not only does the stop-approach procedure artificially heighten participants' awareness of the spatial dynamics of the interaction, thereby altering the natural proxemic process and their preferred distances, but participants also recognize that the environment includes artificial safety measures that may not replicate real-world interaction scenarios. This awareness can influence how participants assess the situation, perceive the drone, and ultimately determine their proxemic preferences, casting doubt on the validity of the findings and their generalizability.

This issue was identified early in the field. In a seminal study on proxemics involving drone flight heights, Duncan and Murphy raised concerns about the questionable validity of their experimental setup, noting the lack of realism in the environment and the explicit disclosure of artificial safety measures to participants [107]. In the first study examining free-flight distancing, Acharya and colleagues echoed these concerns, highlighting the fixed position of the drone which introduced artificial stability not found in real flying drones, thereby affecting participants' perceptions [5]. Yeh et al. [389] also fixed the drone's position artificially using cables, although it remains unclear whether the drone was actively flying or suspended by a cable. If the latter scenario, as noted by Lieser et al. [235], this would significantly limit the study's relevance, as the movement of propellers, resulting downwash, and associated noise profoundly impact participants' emotional responses during human-drone interactions [82].

These constraints in proxemic research amplify those already discussed in subsection 2.1.3, underscoring the necessity for exploring alternative methodologies to study human spatial behavior around drones. This rationale drives our research focus on leveraging VR for human-drone proxemic studies.

2.2.4 Summary and Gaps

This section synthesizes critical insights from the proxemics literature that have shaped our research trajectory and are pivotal for contextualizing the significance of our contributions and the gaps we aim to fill.

- **Proxemics** refers to human spatial behavior and the use of space. It is a mostly unconscious, dynamic behavior influenced by individual and context-dependent sensory perceptions, serving various non-exclusive functions: Communicative [24, 163], Protective [96, 103, 336], Arousal Regulation [122, 282], and Action-Oriented [66, 89, 96, 163].

- **Various methodologies** exist to study proxemics, each offering different levels of control, realism, and validity. These include projection methods, quasi-projective methods (such as the Stop-Approach procedure), interactional methods, and the use of immersive virtual environments. Quasi-projective techniques are widely used due to the high control they offer. However, interactional methods are preferred for obtaining generalizable results, as they involve observing human behaviors in natural interactions without individuals being aware that their spatial behavior is under scrutiny. This level of realism and validity is difficult to achieve with projection or quasi-projective methods. Interactional methods, while more valid, offer less control and pose measurement challenges. Consequently, proxemic studies have increasingly been conducted in immersive virtual environments, which provide a balance of high control and realism while allowing accurate measurement of proxemic behaviors in interactional settings.

- **A lack of theoretical foundation** currently hinders the development of cumulative knowledge in human–drone proxemic research. Current research on human-drone proxemics mainly addresses proximate explanations, describing the determinants and causes of the phenomenon, with little theoretical consideration, thereby repeating mistakes from human-robot proxemic research [227]. There is a need for the field to shift towards proposing ultimate explanations—explaining why these observations occur in the first place. This approach would allow empirical findings to achieve their maximum potential research value by setting expectations using relevant theoretical frameworks and determining whether new empirical findings are confirmatory and integrate well with existing research, or are surprising and require further replication and scrutiny [264]. This perspective motivated our approach to answering RQ1. We aim to lay the theoretical foundation needed in the field by examining the role of multiple proxemic functions in HDI and building a generic model encompassing all these functions. This will contribute to an accessible, theoretically grounded, and empirically supported model that experimenters can refer to when motivating their studies, predicting, and explaining their results, ultimately moving towards a more comprehensive understanding of human-drone proxemics over time.

- **Methodological limitations**, particularly those related to the potential dangers of drone proximity, significantly hinder experimenters' ability to conduct valid proxemic studies. Safety requirements often lead to prioritizing control over realism, which can jeopardize the validity of the measurements. Researchers tend to overly rely on the stop-approach procedure, with very few interactional studies, and use visible safety measures that inevitably alter participants' perception of the situation and potentially affect proxemic outcomes. As with human-human proxemic studies, the use of immersive virtual environments (IVEs) is very promising, as it addresses these issues and the broader ones highlighted in section 2.1. However, IVEs remain marginally used in the field, possibly due to a lack of understanding of how to use them effectively to gain valid insights into human proxemics. These methodological issues and the apparent lack of understanding of how to use VR motivated RQ2. The following section delves into Virtual Reality.

The upcoming section provides an overview of Virtual Reality (VR) technology, covering its evolution, current capabilities, core concepts, and its application to human-drone proxemics. It discusses the potential benefits of VR in addressing current limitations within the human-drone proxemic field, along with its inherent limitations and associated mitigation techniques.

2.3 Virtual Reality

In this section, we will begin by presenting an overview of Virtual Reality (VR) technology, including its historical evolution, current capabilities, and fundamental concepts and use in research. Subsequently, we will discuss the potential for VR in addressing challenges within human-drone proxemics, highlighting its potential transformative impact while also examining potential constraints.

2.3.1 Overview

A Brief History

The evolution of Virtual Reality (VR) has progressed through several distinct waves, each marked by significant technological advancements. In the 1960s, the first prototypes of what would later be called Virtual Reality emerged. Morton Heilig's Sensorama in 1962 [171] combined 3D visuals, sound, and other sensory inputs to create immersive experiences, while Ivan Sutherland and Bob Sproull's The Sword of Damocles in 1968 [343] introduced the first head-mounted display (HMD) system, although it was rudimentary and cumbersome.

However, it was not until 40 years later that the world experienced the first wave of Virtual Reality. In the 1990s, new VR systems such as the Virtuality gaming system in 1991 [196], which featured HMDs and real-time graphics, and the CAVE Automatic Virtual Environment in 1992 [92], which used projection-based VR for scientific applications, presented unprecedented technological capabilities and financial accessibility. These advancements captured researchers' attention. Seeing beyond the current limitations, researchers focused on the very concept of Virtual Reality, defined as the externally mediated presentation of sensory stimuli that enables a person to perceive an artificial environment as non-synthetic to varying degrees [306]. In 2002, Blascovich [47] asserted that VR would eventually address well-known methodological issues in social psychology, offering high control and mundane realism, high replicability, and the ability to target more representative samples. Despite the initial excitement fading due to technological and accessibility limitations, researchers continued to develop a deeper understanding of VR, contributing pioneering works.

The second and current wave of VR began with the 2012 Oculus Rift Kickstarter project [274], aiming to provide an affordable high-quality Head-Mounted Display (HMD) to the public. This initiative sparked a democratization and innovation movement, with tech giants like Meta and numerous startups entering the field. This wave is characterized by a rapid pace of technological innovation. From the beginning of this thesis in 2021, to the present in 2024, the technological landscape has changed significantly. One recent review of VR technology aptly noted, "When you read this publication, it will most likely be out of date" [23]. This might be true when you read the next subsection about current VR's capabilities (see section 2.3.1). Its success relied not only on its affordability and technological capabilities but also on the significantly easier application of this technology in various projects. Free and user-friendly software like Unity 3D and Unreal Engine enables the creation of virtual environments, while Blender 3D allows for the development of detailed 3D models. Even without a background in computer science, anyone can easily access numerous free courses and a vast array of online resources. These resources include fully interactive virtual environments [358], specific code snippets for tailored purposes, and high-quality, sometimes animated, 3D models (e.g., Mixamo [9], Rocketbox Library [152]). The recent advent of powerful natural language processing tools like OpenAI's

ChatGPT further facilitates each of these aspects. Today, VR is accessible to anyone and can be used to create highly immersive, interactive, and customizable experiences, making it a versatile tool for a wide range of applications.

Current Capacities

Virtual Reality (VR) technology today offers a broad and sophisticated range of capabilities that enable immersive and interactive experiences across various fields. Here's an overview of what is feasible with current VR technology:

- **Immersive Environments**
  - *High-Resolution Displays*: Modern VR headsets offer high-resolution displays, often exceeding 4K resolution per eye, which provides clear and detailed visuals, enhancing the sense of presence [384].
  - *Wide Field of View*: Many headsets feature wide fields of view, ranging from 100 to 130 degrees (e.g., 110 for the Meta Quest 3) making the virtual environment more encompassing and realistic [247].
- **Tracking and Interaction**
  - *Six Degrees of Freedom (6DoF)*: VR systems support 6DoF tracking, allowing users to move freely in physical space and have their movements accurately mirrored in the virtual environment [220].
  - *Inside-Out Tracking*: Cameras on the headset track the user's position without external sensors, simplifying setup and improving mobility.
  - *Hand Tracking*: Advanced hand-tracking technologies allow users to interact with virtual objects using natural hand movements, without the need for controllers [64, 364].
  - *Eye Tracking*: Eye-tracking capabilities enhance interactivity and realism by allowing the system to respond to where the user is looking, enabling foveated rendering, which optimizes graphics performance [6].
- **Sensory Feedback**
  - *Haptic Feedback*: Although not yet available with commcercial headsets, companies and researchers have presented haptic devices and gloves provide tactile feedback, enabling users to feel virtual objects, enhancing the sense of immersion [285, 367].
  - *Spatial Audio*: High-quality spatial audio systems create realistic soundscapes that change dynamically based on the user's position and orientation in the virtual environment [39, 146, 292].

- **Augmented Reality (AR) and Mixed Reality (MR)**
  - *Passthrough Capabilities*: Advanced headsets, like the Meta Quest 3, offer high-quality passthrough features that blend the virtual and real worlds, enabling mixed reality experiences where digital objects interact with the real environment [157].
- **Software and Development Tools**
  - *Development Platforms*: Platforms like Unity 3D [193, 357] and Unreal Engine [83, 142] provide robust tools for creating complex and interactive virtual environments, supporting a wide range of applications from games to simulations.
  - *3D Modeling and Animation*: Tools like Blender 3D allow for the creation of detailed 3D models and animations that can be imported into VR environments, enhancing the realism and interactivity of the content [135, 181].
  - *Free Online Resources*: There are numerous free online resources available for learning VR development and 3D modeling. Courses on platforms like Coursera, and YouTube, along with extensive libraries of free assets and code packages, make it easier for researchers and developers to get started with VR without needing a background in computer science.
  - *AI Integration*: The integration of AI, such as natural language processing (NLP) and machine learning, enables smarter and more responsive virtual characters and environments, facilitating more dynamic and personalized user experiences.
- **Data Collection and Analysis**
  - *Behavioral Data*: VR systems can collect detailed data on user interactions, movement patterns, and gaze behavior, providing valuable insights for research and development [179, 287, 388].
  - *Physiological Monitoring*: Some VR setups can integrate with biometric sensors to monitor heart rate, skin conductance, and other physiological indicators, allowing for more comprehensive analysis of user responses [161, 372].

These advancements collectively enable VR to provide highly immersive, interactive, and customizable experiences, making it a versatile tool for a wide range of applications.

Core Concepts

Virtual Reality (VR) encompasses several core concepts that describe different aspects of the virtual experience. The most prominent concept is *Presence*, which refers to the feeling of being physically present in a virtual environment, despite knowing it is computer-generated. Achieving high presence enables participants to respond realistically to the virtual reality [330, 332], which is crucial for research applications. The generalizability of any study's results depends on how well the experimental paradigm represents "real" experiences [306]. For a comprehensive review of presence and its related concepts, see [327] and [126].

The *Place Illusion* (PI) and *Plausibility Illusion* (Psi) model proposed by Slater [327, 330] provides a framework to understand how VR achieves high levels of presence. Place Illusion is the sensation of being in a place despite knowing you are not there physically. Plausibility Illusion refers to the feeling that the events occurring in the virtual environment are actually happening, influenced by the system's ability to respond credibly to user actions and environmental interactions. Together, these illusions contribute to a convincing VR experience by ensuring the virtual world behaves in a way that aligns with the user's expectations and actions. Achieving high levels of Place Illusion and Plausibility Illusion suggests that participants will respond realistically to the virtual reality [330].

Place Illusion is achievable through *Immersion* [327], which relates to the objective properties of a system and the extent to which it can support natural sensorimotor contingencies (SCs) for perception. SCs refer to the actions we perform to perceive, such as moving our head and eyes to change gaze direction or bending down and shifting our gaze to see underneath something [277]. Factors related to immersion include hardware specifications that enable natural visual perception, such as display resolution [144, 238], field of view (FOV) [20, 238], depth perception enabled by stereoscopic displays [186], head tracking, frame rate [252], auditory feedback [365], and haptic feedback [201]. Greater immersion leads to higher place illusion.

Plausibility Illusion refers to whether the virtual environment and its responses to participants' actions appear coherent. It can be influenced by content determinants [126] such as the narrative of the VR environment, with reports suggesting that cohesive narratives tend to increase virtual presence [153]. Environmental realism is crucial, not in terms of fidelity but in whether it "plausibly reflects events that do or could occur in the non-mediated world" [240]. Interestingly, there may be interactions between these determinants, as supernatural abilities like teleportation, invisibility, or flying experienced in a science-fiction or fantasy context would be regarded as coherent behavior [194]. Other factors include avatars' appearance [366] and real-world sensory distractions [368].

An important distinction needs to be made regarding the concept of presence in virtual reality. It is sometimes described as the belief that something is real when it is not. However, as Slater [331] pointed out, this is misleading and inaccurate. When someone stands by a virtual precipice with their heart racing and feeling intense anxiety, they do not actually believe in the reality of the virtual environment. Instead, what has been effectively induced is the feeling of presence—the illusion of being there. This distinction is crucial for understanding the true nature and power of presence in VR.

That being said, presence remains a subjective experience [101]. While the immersion and coherence of the virtual environment are largely under the control of the developer, internal factors [280] such as personality traits [99, 184] are not, and can influence the ultimate presence output [126, 327]. Fortunately, there are ways for experimenters to assess the validity of their virtual environment a posteriori by measuring participants' presence level. While there isn't a widely accepted and validated measure of virtual presence yet, researchers employ a wide range of measurement techniques, including subjective, behavioral, physiological, neurological, and task-based measures [126]. Among subjective measures, the most commonly used are post-immersion questionnaires such as the Igroup Presence Questionnaire [315, 316], administered after or within the simulation [317].

With this foundation in place, we can now transition to exploring how the advanced capabilities of VR technology can be applied to human-drone proxemics.

2.3.2 Virtual Reality For Human–Drone Proxemic Studies

Virtual Reality (VR) as a research methodology draws researchers' attention for years. In 1999, Loomis et al. [241] introduced VR as a promising solution to the issues of its field. It would "eliminate the trade-off between mundane realism and experimental control, [...] target population more representatively and reduce the difficulty of replication" [47]. Since then, virtual environments have been extensively used in Social Psychology [306], in Human–Computer Interaction (HCI) [88, 248, 265] or Human–Robot Interaction (HRI) [307, 377]. Since its first research applications in the 1990s, the technology has significantly progressed and presents itself as a very attractive alternative to real-world studies. It remains however marginaly used in HDI. Wojciechowska et al. [382] ranked it as the second-best method for investigating human-drone interactions following real-world collocated flight, and Cauchard et al. [77] used VR to explore novel drone designs.

It is noteworthy that one of the first uses of virtual reality in social psychology research was to study proxemics [31]. With the emergence of the field of human-drone interaction, virtual reality has once again become a promising tool for proxemics research. The technology and the opportunities it offers are particularly appealing for this area of study [47, 227]. The next paragraph will briefly explain how VR can address many of the significant limitations in studying human-drone proxemics. However, there are potential differences in the observed phenomena compared to real-world scenarios. It is important to highlight these differences and develop techniques to minimize them, which will be discussed in the subsequent section. Given the multiple underlying behavioral mechanisms that could influence proxemic behaviors during human-drone interactions (see section 2.2), we will elaborate on their specifics when presenting the studies associated with each of these mechanisms in the following chapters.

Promises for the Field

Virtual Reality application to Human–Drone Proxemics is particularly relevant as the field suffer from many limitations associated with real-world constraints, that VR could easily address.

- **Balancing Control and Realism**: Traditionally, human-drone proxemics research has relied heavily on controlled settings at the expense of interaction realism. This often involves using quasi-projective techniques, such as the Stop-Approach Procedure, rather than more valid interactional methods, typically conducted in indoor environments with safety measures in place. Several factors contribute to this approach, including improved accuracy of measurements, replicability, participant safety, and simpler experimental setups. While this level of control is often necessary, it can significantly undermine the validity and generalizability of the results due to the methods employed and the altered perception of the situation for participants. Virtual Reality, however, offers a solution by enabling full control over the experimental environment while maintaining a high level of realism. Virtual Environments are inherently safe, there is no need for additional techniques. Moreover, today's technology enables users to freely move within a virtual space, naturally walking if they have enough space in the real-world, or using locomotion techniques if not.

- **Simple Complex Interactions**: Another reason for prioritizing the Stop-Approach Procedure over interactional methods is the complexity of implementing real-world interactions with drones. These interactions can be difficult to program, impacted by hardware limitations (e.g., battery life, sensor unreliability), and challenging to replicate accurately. VR allows researchers to easily deploy and explore various interaction techniques in a perfectly controlled setting, free from technological constraints and with high replicability. Additionally, VR provides the capability to collect numerous inputs from participants, such as eye and hand tracking, external input devices, facial expressions, body tracking, and movements, that can be used for interaction.

- **Enhanced Measurement**: Investigating human-drone proxemics requires precise measurements of participants' behavior, particularly the distance maintained between the subjects of interest. While this distance is easily obtainable with the Stop-Approach Procedure, it becomes challenging to measure in more natural settings typically found with interactional methods. This challenge is mitigated in virtual environments, where the positions of virtual objects and participants, along with other potential data of interest, can be collected over time. VR's potential is especially apparent in more natural settings, enabling a significantly richer assessment of participants' proxemic behaviors compared to the limited single stop-distance measurement usually employed in human-drone proxemic studies using the Stop-Approach Procedure.

- **Expanded Research Possibilities**: Human-drone interaction studies often use a limited number of drones that vary in size but are generally similar in appearance and functionality. Researchers have highlighted the need to explore different types of drones. However, experimenters are constrained to use what is available on the market, leading to a slow pace in investigating innovative drones. Virtual Reality (VR) allows researchers to model any type of drone they can imagine, incorporating social features and controlling factors that cannot yet be technologically controlled, such as the sound of the drone. Virtually anything is possible in VR. Additionally, while most research is conducted in controlled indoor settings with limited consideration for real-world deployment, VR can be used anywhere, recreating any desired environment from a park to a hospital, but also using real-world one with passthrough features, only augmenting objects of interests such as the drone. Given that there's no actual drone flying, legal constraints disapear. This allows for the exploration of virtually any setting and address the lack of consideration for contextual factors outlined in previous works. Overall, VR empowers researchers to explore a comprehensive research space, facilitating investigations into nuanced aspects of human-drone interactions that are currently unfeasible or impractical. These capabilities pave the way for innovative studies and a deeper understanding of the complexities inherent in Human-Drone Proxemics research.

In conclusion, the application of Virtual Reality to Human-Drone Proxemics holds profound promise for advancing research in this field, which is often constrained by the limitations of real-world settings. VR addresses critical challenges by offering a balanced approach between control and realism, overcoming the shortcomings of traditional methods like the Stop-Approach Procedure. By providing a safe, controlled environment where complex interactions can be simulated and measured with precision, VR enhances the validity and breadth of human-drone interaction studies. Moreover, VR expands research possibilities by enabling the exploration of diverse drone types and environments, unrestricted by real-world constraints and legal considerations. This capability not only broadens the scope of investigation but also enriches our understanding of proxemic behaviors in contexts that are otherwise difficult or impractical to study. While virtual reality holds appeal, its relevance for research hinges on the extent to which observed phenomena mirror real-world observations, which is discussed in the following section.

Mitigate its Limitations

While virtual reality holds appeal, its relevance for research hinges on the extent to which observed phenomena mirror real-world observations. Therefore, it's crucial that participants react naturally to the stimuli presented. In the context of studying human-drone proxemics, VR must ensure that participants perceive and respond to drones in a manner akin to real-world interactions. Without taking this for granted, it's imperative to assess VR's potential impact on various proxemic processes and devise strategies to mitigate any distortions. We will explore hereafter how VR may influence established proxemic factors of distance perception and motor abilities and propose effective mitigation techniques. Given the multiple underlying behavioral mechanisms that could influence proxemic behaviors during human-drone interactions (see section 2.2), we will elaborate on their specifics when presenting the studies associated with each of these mechanisms in the following chapters.

Previous Comparison Comparing proxemic preferences and impressions of a humanoid ground robot between a real and virtual environment, Kamid et al. [197] did not find significant differences in terms of desired space despite different subjective impressions. Conversely, Li et al. [230] found inconsistent proxemic preferences between Live and VR ground robots but no major changes between different VR settings. These mixed results and the lack of theory-driven explanations leaves a gap of uncertainty regarding the validity of VR for Human–Robot proxemic experiments. In addition, drones are drastically different from ground robots. As suggested by a previous direct comparison [5], the driven mechanisms of people proxemic may be different between ground and flying robots, involving different considerations for the use of VR for proxemic experiments.

From a theoretical standpoint, considering proxemic behaviours rely on the perception and interpretation of sensory inputs, any alterations of these two aspects could change the ultimate proxemic output.

Distance Perception A crucial high-level cue in proxemic behavior is distance perception, which involves individuals' ability to estimate the space separating them from their surroundings. This estimation is very intuitive, similar to how we can easily determine whether an object is within reach from a fixed position. In a recent meta-analysis of the effect of head-mounted display (HMD) characteristics on distance perception, Kelly and colleagues [202] found that judged distance was positively associated with HMD field of view (FOV), positively associated with HMD resolution, and negatively associated with HMD weight. They highlight a general increase in accuracy over the years due to lighter headsets, wider FOVs, and increased resolution. The average accuracy for the Oculus Rift CV1 (FOV: 110 degrees, Resolution: 1080×1200) was 86% at the time of Kelly's review. It is expected that more recent headsets with improved specifications will yield even better accuracy.

Similarly, Masnadi and colleagues [247] observed better perception accuracy with higher FOV but noted no significant differences between 200 and 110 degrees, suggesting the positive benefits of FOV may reach a ceiling and that other factors might impact distance perception. Interestingly, other researchers have found that replicating the real-world environment within which the study is conducted significantly improves distance estimation [187, 203, 339]. Interrante and colleagues [187] showed that in a high-fidelity, low-latency, immersive virtual environment that represents an exact virtual replica of the participant's concurrently occupied real environment, distance perception appears not to be significantly compressed in the immersive virtual environment relative to the real world. Similarly, a more recent study reported no significant difference in distance estimation between a real environment and its virtual replica using an Oculus Rift headset (FOV: 94 degrees, 1920×1080 resolution) [125]. However, the study did find that discrepancies between estimates of real and virtual distances increased with the incongruity between virtual and actual eye heights, demonstrating the importance of accurately setting virtual eye height . Additionally, research indicates that it is possible to train the accuracy of distance estimates in virtual environments by providing participants with a few minutes of feedback-based practice [21].

These findings suggest that reporting the specifications of the HMD used in virtual proxemic studies is highly important. To greatly minimize or completely remove distance compression within VR, researchers should:

1. Use recent lightweight HMDs, such as the Meta Quest 3, which has a 110-degree FOV and 2064x2208 resolution per eye.

2. Employ an accurate replica of the real-world setting in which the study is conducted. A pertinent question is: How accurate does it need to be? Skarbez et al. [328] state that the perceived authenticity of a virtual replica largely depends on the room's scale and the alignment of large objects with their real-world counterparts. Therefore, ensuring similar dimensions and placing salient visual cues in both the real and virtual environments should help maximize the perception of authenticity.

3. Include a familiarization phase during which participants can walk and naturally experience distances. This phase should continue until participants feel confident navigating the virtual space, as lack of confidence in the replication accuracy can lead to altered behaviors, as discussed in the following paragraph on motor abilities.

4. Avoid incongruency between virtual and actual eye heights. This can be achieved through the headset's calibration phase, which typically involves identifying the floor level. To verify accuracy in the virtual environment, place the tracked hand or controller on the ground and check if it aligns with the virtual ground. If there is a mismatch, the experimenter should recalibrate the floor position.

By following these guidelines, researchers can ensure more accurate and reliable distance perception in virtual environments.

Motor Abilities Virtual Reality can potentially affect individuals' perceived or actual motor abilities, meaning their ability to move or perform actions. Participants might be concerned about colliding with real-world objects while immersed in the simulation, leading them to navigate with less confidence in the virtual environment. Additionally, using a headset connected to a computer with cables can physically limit participants' movements. If they can feel the cable, it might make them more cautious about not stepping on it or raise concerns about the cable's length. These alterations could influence the ultimate proxemic output, resulting in more space being maintained if participants feel less able to react quickly [147].

Research on the use of VR for pedestrian behavior studies provides insights into this issue. Recent comparative studies report similar behaviors between real and virtual environments. However, when comparing object avoidance, Fink et al. [128] and Sanz et al. [310] found that participants maintained more distance and moved more slowly around virtual objects than in real environments. These results, however, are not easily generalizable to modern immersive virtual environments, given that both studies used the CAVE system, which differs significantly from VR headsets, and did not provide information about distance compression.

In a similar study using a VR headset, Gérin-Lajoie and colleagues [160] reported more positive results. They found that all participants quickly learned to navigate the virtual environment (VE) at their natural unobstructed speed. The overall shape of the participants' personal space (PS) was similar between real and virtual environments, although subjects slightly enlarged their PS in the VE. One possible explanation mentioned by the experimenters for this increase in PS could be the limited FOV in the HMD. We now know that a low FOV can induce distance compression, leading to more space being maintained as objects appear closer. In their 2008 study, they used a heavy headset with a restricted 40° horizontal FOV.

Another factor that may impact people's motor abilities is the locomotion technique used. To our knowledge, there are no previous studies on how different locomotion techniques impact proxemics. However, controller-based locomotion has been shown to induce greater cybersickness compared to natural walking or teleportation [218]. Since teleportation is not ideal for observing natural proxemics, we consider that natural walking should always be preferred. Nonetheless, while actually walking in the virtual space is more natural, it inevitably means we are limited by the real-world space available for the study. For this reason, there is great potential for fixed physical motion such as walking in place [50]. The recent Holotile presented by Disney holds promise in this aspect [102].

These findings suggest that to minimize the impact of VR in participants' motor abilities, researchers should:

1. Use standalone headsets or implement efficient cable management to prevent physical hindrance to participants' movements.

2. Utilize a room-scale environment with natural physical walking as the locomotion method to enable natural navigation and proxemics while preventing cybersickness.

3. Ensure the virtual environment only includes spaces accessible in the real world to prevent

collisions and maintain participants' trust in the simulation.

4. Allow participants to familiarize themselves with the virtual environment to gain confidence in their ability to navigate the space and assess its accuracy.

5. Follow the guidelines presented in the previous paragraph to minimize distance compression.

By following these guidelines, researchers should prevent significant alteration of participants motor abilities in virtual environments

Perception of the Virtual Drone Accurately assessing proxemics requires that participants respond naturally to the stimuli of interest. A key question is how to design the virtual drone so that people naturally respond to it. The literature on VR is encouraging, with studies showing that people perceive and respond naturally to threatening virtual objects [86], social agents [32], and specific situations such as public speaking [84, 333], phobias [306], and other scenarios [246]. This suggests that people can perceive a virtual drone as real.

According to the Place and Plausibility Illusion Model by Slater [330] and supported by the Threshold Model of Social Influence in Digital Virtual Environments (TMSI) [47, 306], movement realism is more crucial than photographic realism. Participants are more likely to perceive an entity as real if it subjectively behaves realistically. Therefore, we should observe real drones and replicate their behavioral characteristics, including flying movements and rotating propellers. Since proxemics rely on the perception of sensory inputs, the visual aspect of the virtual drone also matters. It should look similar to its real-world counterpart in terms of color, shape, dimensions, visible propellers and guards, and overall structure. It has been shown that visual realism enhances realistic responses in an immersive virtual environment [332]. Additionally, in line with the plausibility illusion and to increase the fidelity of the sensory experience, the virtual drone should also emit realistic sounds. If we achieve high levels of physical presence and the participants' experiences within the virtual environment match their expectations of reality (Plausibility Illusion), previous work suggests participants will respond realistically to the virtual reality [330].

Ultimately, the virtual drone should look, behave, and sound realistic to participants to enable natural responses from them.

Other Aspects In this literature review, we addressed initial concerns about using VR to study human-drone proxemics and provided emerging guidelines to shape our initial virtual user studies. However, additional study-specific aspects must be considered. The generalizability of any study's results depends on how well the experimental paradigm represents "real" experiences and interactions outside the laboratory [306]. Therefore, for each study, it is crucial to consider whether the independent variables we aim to examine will elicit responses that reflect participants' real behaviors. For example, if participants are performing a specific task, their motor abilities for that task must be taken into account. If we are studying defensive behaviors, perceived threat levels are crucial, so we need to understand whether similar threat levels are perceived in VR. Overall, it is essential to consider how VR could impact all aspects that might influence proxemic outcomes within the theoretical framework and to minimize these influences. This approach must be tailored to the specificities of each study. Given the multiple underlying behavioral mechanisms that could influence proxemic behaviors during human-drone interactions (see section 2.2), we will elaborate on their specifics when presenting the studies associated with each of these mechanisms in the following chapters. The next subsection summarizes this literature review on Virtual Reality, highlighting its definition, benefits, and limitations.

General Experimental Setup

Across our studies, we employed a consistent experimental setup following the guidelines outlined above. To avoid redundancy, this section describes the common elements shared across experiments, which will be referenced throughout the manuscript. Additional practical details and guidelines can be found in section 8.6.

Virtual Environment The experiments took place in immersive virtual environments (IVEs) designed in Unity 3D. This approach was chosen to circumvent the technical, design, and safety challenges commonly encountered in real-world Human-Drone Interaction (HDI) experiments [58,107,235] and leverage its benefits for the field. The Unity projects are available in the Thesis GitHub repository [56].

To ensure ecological validity, the virtual environments faithfully replicated the dimensions and layout of the actual experimental rooms, allowing participants to perceive them as accurate representations of reality [328]. This fidelity was crucial for enhancing the sense of presence, Place Illusion [335], and mitigating perceived distance compression [187], which is essential for proxemic studies. By aligning participants' real and virtual positions, we enabled free movement within the environment without obstructions such as cables or virtual barriers, ensuring natural locomotion akin to real-world conditions. Following prior proxemic research using VR [31, 57], we leveraged the VR headset's positional data to track participants' movements and assess proxemic behavior across experimental conditions.

To foster Plausibility Illusion—the perception that the virtual environment and its responses are coherent—we implemented several measures: eliminating external distractions [368], framing the experience with a coherent narrative [153], developing a high-fidelity virtual replica of the real environment [126], enabling hand-tracking or controller visibility [366], and providing haptic feedback upon contact with walls and tables. These steps aimed to enhance the plausibility of the experience.

That said, presence remains a subjective experience [101]. While environmental immersion and coherence are controlled by the developer, internal factors such as personality traits [99,184] also influence perceived presence [126,327]. This motivated the inclusion of the Igroup Presence Questionnaire to evaluate participants' subjective experience of presence [315].

The VR headset models (Meta Quest 2, 3, and Pico Neo 3 Pro Eye) and control methods (hand-tracking or controllers) varied between studies and will be detailed accordingly. Additionally, the experiment presented in chapter 6 employed a different setup, which will be described separately.

Drone Design While the drone design shares similarities across studies, variations in control modes, 3D models, and other specifics often differ. Therefore, we provide full details within each study.

2.3.3 Summary and Gaps

This section synthesizes critical insights from the Virtual Reality literature that have shaped our research trajectory and are pivotal for contextualizing the significance of our contributions and the gaps we aim to fill.

- **Virtual Reality** (VR) refers to the externally mediated presentation of sensory stimuli that enables a person to perceive an artificial environment as non-synthetic to varying degrees [306]. The substantial advancements in VR technology [23] and the improved understanding of how participants experience virtual environments and how to elicit natural responses [126, 327] make it an appealing alternative to real-world studies [306]. By understanding and harnessing both the technology and its associated psychological concepts, researchers and developers can optimize VR experiences to achieve desired outcomes effectively. Its fast-paced evolution suggest a promising future for its use in research. As VR becomes more accessible and widely adopted, concepts such as remote VR studies [249], which enable valid user studies with participants around the world, are closer to becoming a reality than ever before.

- **For Human–Drone Proxemics**, VR has the potential to offer controlled and realistic experimental settings. This enables the use of interactional methods, which are more valid for studying proxemic behaviors [11], while also allowing for precise measurement of participants' proxemic responses. Additionally, VR addresses numerous limitations associated with real-world proxemic studies, including restricted design options, technological constraints, complexity, legal issues, and safety concerns. Nonetheless, VR remains marginally used in this field [382], potentially due to a lack of precedent and understanding on how to utilize it effectively for valid proxemic observations, which is the gap we aim to address.

- **VR's validity** and relevance and for research hinges on the extent to which observed phenomena mirror real-world observations [306]. Therefore, it is crucial that participants react naturally to the presented stimuli. In the context of studying human-drone proxemics, VR must ensure that participants perceive and respond to drones and behave within the virtual environment in a manner akin to real-world interactions. Existing research on sensory perception in virtual environments provides guidelines to minimize distance compression often found in VR [187, 202, 203]. We also identified how to enable participants to navigate the space naturally and without constraints, ensuring their motor abilities remain similar to real-world conditions. Maximizing place and plausibility illusion through high immersion and coherence should enable high presence and natural responses [330], while also providing an illusion of the drone's realness through the replication of its associated sensory inputs. These guidelines will shape our virtual studies, but additional ones will be developed when investigating specific proxemic functions and their associated behavioral mechanisms, such as defensive behaviors.

2.4 Summary and Gaps

This section summarises the literature review with the aim to synthesize the train of thought that lead to our research questions and motivated our course of action.

1. **Social drones**, defined as autonomous drones operating in inhabited environments, are distinct from piloted drones, as they function independently and thus elicit unique social influences that necessitate specific design and human factor considerations [38]. **Proxemics**, the study of human spatial behavior, has been identified as a crucial design concern for social drones, requiring further investigation.

2. However, a **significant lack of theoretical foundation** in human-drone proxemics impedes cumulative knowledge development. Current research predominantly offers proximate explanations (i.e., identifying influential proxemic factors) without sufficient theoretical grounding, echoing past shortcomings in human-robot proxemics [227]. There is a pressing need to shift towards proposing ultimate explanations that elucidate why observed phenomena occur, enhancing the research value by integrating empirical findings with robust theoretical frameworks [167, 264]. This gap motivated our approach to RQ1, aiming to assess the relevance of multiple proxemic frameworks in HDI and to establish a unified model that describes people's spatial relationships with external entities, including social drones.

3. **Proxemics**, which explores human spatial behavior and the use of space, involves dynamic, mostly unconscious behaviors influenced by individual and context-dependent

sensory perceptions. These behaviors serve various non-exclusive functions: Communicative, Protective, Arousal Regulation, and Action-Oriented. Given that each of these proxemic functions is associated with specific related work, theories, and considerations for HDI, we designed distinct user studies to explore each function in depth and understand their role in HDI. The synthesis of the findings from these studies will contribute to the development of a unified model of human proxemic behaviors in relation to external entities, including drones (see chapter 7). This model integrates all these functions simultaneously and further elaborates on how their interactions shape proxemic outcomes.

4. **Methodologically**, different approaches exist to study proxemics, each offering varying levels of control, realism, and validity. While projection and quasi-projective methods like the Stop-Approach procedure provide high control, interactional methods are preferred for their ability to capture natural behaviors in unobtrusive settings, despite their challenges in control and measurement. Increasingly, immersive virtual environments (IVEs) are being utilized to balance control and realism, enabling precise measurement of proxemic behaviors in naturalistic interactions.

5. **Virtual Reality** (VR) involves the presentation of sensory stimuli to create an artificial environment that users perceive as real to varying extents [306]. Recent advancements in VR technology [23] and improved insights into user experience and ways to elicit natural responses [126, 327] make it an appealing substitute for real-world studies [306]. By understanding and harnessing both the technology and its associated psychological concepts (i.e, Presence, Immersion, Place and Plausiblity Illusion), researchers and developers can optimize VR experiences to achieve desired outcomes effectively. Specifically in HDI and for proxemic studies, VR has the potential to address the many limitations of this field.

6. The field of Human-Drone Interaction (HDI) faces **multiple methodological issues**, with critical limitations in real-world user studies, including safety concerns, complexity, legal constraints, technological limitations, and poor design options. Researchers have emphasized the urgent need for better prototyping and development tools for those working with social drones. Additional methodological limitations for human–drone proxemic studies linked to safety concerns associated with drone's proximity further undermine the validity and generalizability of the results due to the methods employed (e.g., stop–approach procedure) and the altered perception of the situation for participants (e.g., visibe safety measures). One promising approach to overcome these challenges is the utilization of Virtual Reality (VR). Despite its advantages, VR remains underutilized in HDI [382] which may stem from insufficient precedents and understanding of its optimal use for valid proxemic observations, a gap our research aims to fill by demonstrating the optimal use of VR for human-drone proxemics studies, offering guidelines and practical examples to advance the field.

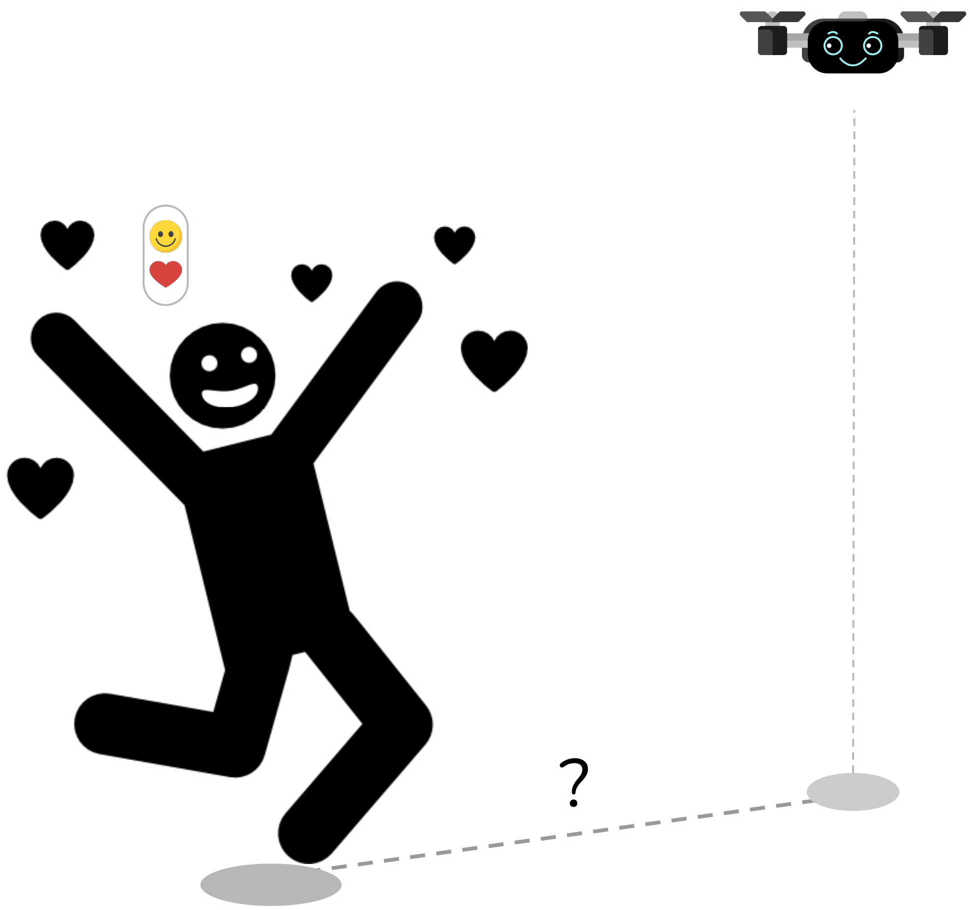
7. **VR's validity** in research hinges on its ability to replicate real-world phenomena [306], necessitating natural participant reactions to stimuli. In studying human-drone proxemics, VR must ensure participants perceive and respond to drones realistically, minimizing distance compression and enabling natural navigation [187, 202, 203]. Enhancing place and plausibility illusions through immersion and coherence promotes presence and natural responses [330], augmenting the perception of drones' realism through accurate sensory replication. These principles will guide our VR studies, with additional insights developed when investigating specific proxemic functions and associated behaviors, including defensive responses.

These preceding points outline the thought process that led to the formulation of our research questions and strategic approach. To address RQ1—"What motivates individuals' proxemic behaviors around drones and how do they manifest?"—we investigate the four potential proxemic functions identified in the literature (i.e., Communicative, Protective, Arousal Regulation, and Action-Oriented). Each of these functions is associated with specific related work, theories, and considerations within Human-Drone Interaction (HDI). Consequently, we have devised distinct user studies aimed at delving deeply into each function to comprehend its role in HDI. These studies are conducted using Virtual Reality (VR), where we rigorously assessed its suitability, identified potential limitations, and devised strategies to mitigate them. This approach enables us to address RQ2—"How can VR be optimally utilized to study human-drone proxemics?"—and harness VR's potential to advance proxemic studies in HDI.

Chapter 3 presents the research conducted to investigate the communicative proxemic function in Human-Drone Interaction (HDI).

Chapter 3

The Communicative Proxemic Function



3.1 Chapter Introduction

Among humans, the space maintained between individuals is an important social cue that provides significant information about the social dynamics at play (e.g., social status, intimacy levels, and social norms) [163]. This social distancing is dynamic and relies on sensory perception, interpretation of social cues [24], the type of activity taking place, and cultural expectations. Importantly, inappropriate interpersonal distancing can induce discomfort, prompt spatial adjustments, and affect people's perceptions of intruders. The communicative proxemic function encompasses these socially driven spatial adjustments, proactively exhibited as communication cues, or aimed at regulating spatial appropriateness in response to external social influences. These influences are defined as the effects of the social significance assigned to others' actions, social status, attitudes, or opinions on an individual's behavior and decision-making.

3.1.1 Motivation

Why Assessing the Communicative Proxemic Function? In Human-Robot Interaction (HRI) and Human-Drone Interaction (HDI) studies, Hall's theory of proxemics [163]—focusing on the social use of space—is often the default framework to explain observed distancing behaviors. While this theory has been successfully applied to ground-based robots, particularly humanoids, which are perceived as social agents with considerable social influence [43, 263], the unique nature of flying robots introduces a different paradigm. The challenges and opportunities posed by drones demand a shift in how we understand the development of flying social robots.

This communicative proxemic function is only applicable to HDI if one assumes that people's behaviors around drones are socially driven—that drones are perceived as social actors, their cues interpreted in social contexts, and distancing behaviors reflecting intimacy or social appropriateness. However, this assumption may not hold due to the mechanical, non-humanoid nature of current drones [227]. Additionally, there is no conclusive evidence in existing HDI studies regarding drones' capacity to exert significant social influence that triggers behavioral changes. While some research suggests drones may have such influence [172,389], other studies indicate they do not [107].

Moreover, previous HDI research methods, including surveys [172] and stop-approach procedures [107, 389], often rely on unrealistic experimental settings, raising concerns about the validity and generalizability of their findings. As a result, the role of the communicative proxemic function in HDI remains unclear.

Given these limitations, more rigorous research is needed to assess whether drones can indeed exert social influence, as Hall's theory presupposes. Clarifying this would be crucial for the design of social drones, as it would allow designers to incorporate social elements into autonomous drones, activating social mechanisms that enhance user engagement, well-being, and overall interaction quality [54,90].

3.1.2 Overview of the Studies

Study #1 To address this gap in the literature, verify the assumption that autonomous drones are perceived as social entities, and investigate the supposed role of the communicative proxemic function in HDI, we conducted an initial user study in Virtual Reality. In this study, participants naturally navigated around a drone while performing a task (interactional method, see section 2.2) under various conditions identified as proxemic factors (Height and Framing) in human-human and human-robot proxemics, as well as one previously explored in Human-Drone proxemics using questionable methods. Instead of merely providing proximate explanations and describing new proxemics determinants as done previously, we aim to propose ultimate explanations—clarifying why these observations occur. We set our expectations using Hall's theoretical frameworks and assess whether the obtained empirical findings confirm and integrate well with existing research, or are surprising and require further replication and scrutiny [264].

The first factor, flying height, significantly impacted proxemic behaviors, but not as expected through the communicative function. Contrary to the hypothesis that greater height would indicate more dominance and result in more maintained distance, we found that the higher the drone was, the closer people approached. This behavior can be explained through the defensive proxemic function detailed in chapter 4. Cues related to other proxemic functions were noted, providing initial observations that motivated subsequent dedicated studies exploring each of these functions in depth.

Additionally, presenting the drone as a positive social entity (as opposed to a technical presentation) significantly improved participants' initial perceptions of the drone. However, this favorable perception did not persist during the interaction, and no significant proxemic differences were observed. Participants predominantly viewed the drone as a mere obstacle. We attributed this failure to establish a social connection, to the drone's highly mechanical and non-social nature, a conclusion supported by participant feedback. After the social presentation, participants were prepared to engage with a social drone and, although they struggled to articulate their expectations, they clearly anticipated something distinct from the conventional AR Drone 2.0 used in the study. This suggests that traditional drones, with their mechanical nature, are not designed for social interactions, confirming our initial doubts on the relevance of the communicative proxemic function (i.e., Hall's framework) in HDI, and refuting the assumption that drones are perceived as social entities.

Study #2 That being said, despite struggling to concretely describe their expectations, participants in the first study still anticipated interacting with a social drone. This indicates that a design space exists where drones can be perceived as social entities, but it has yet to be revealed. This spark of potential and fitting opportunity to demonstrate Virtual Reality's capacity to expand research possibilities beyond real-world limitations, motivated us to conduct a second user study on the communicative function. Given that the lack of human-like features contributed to categorizing drones as cold machines devoid of social nuance—creating a barrier to establishing meaningful social connections with them—we decided to implement a virtual drone with a digital face. We assessed how different digital facial expressions and gaze behaviors would influence participants' perceptions of the drone and their proxemic behavior.

Our results highlight the context-dependent significance of the communicative function in HDI. People spatially respond to drone social cues similarly to how they react in human–human interactions, but only when engaged in a social interaction. Overall, participants did not establish a strong connection between the drone's expressions and what the drone thought of them or their surrounding environment. They perceived the drone's expressions as relatively context-neutral and abstract, lacking specific relevance to the interaction context. While participants easily recognized these expressions, the ability of these cues to convey nuanced emotional content or context-specific messages seemed limited.

Nonetheless, this work sheds light on how the social proxemic function influences individuals' personal space boundaries in human-drone interactions, beginning to peel back the layers that obscure the social design spectrum for drones, showcasing the initial steps in uncovering this intriguing realm, facilitated by the use of VR.

This chapter details the research that led to these findings.

3.1.3 Chapter Structure

This chapter follows the logical flow presented above in the introduction. First, we will present the initial study (based on [57]), beginning with a brief introduction that highlights the primary motivations, the research questions addressed, and the related work specific to this study. This will be followed by a detailed description of the methodology employed, leading into the reporting of results and analyses. We will then discuss the main findings. A transition will logically connect these discoveries to the second study (based on [60]), which will be presented in the same manner. The chapter concludes with a summary that encapsulates the objectives and main findings of our research. Following this summary, we provide detailed responses to RQ 1.1, "What is the role of the Communicative Proxemic Function in HDI?" based on the findings. Additionally, we offer partial answers to RQ 2, "How can VR be effectively used to study human-drone proxemics?" and RQ 1.5, "How do multiple proxemic functions interact in HDI?"

3.2 *Study #1* - Social Entities or Mechanical Objects?

3.2.1 Motivation

As autonomous drones begin to operate in social settings, they must navigate in ways that are socially acceptable and safe. While numerous studies have examined proxemics in the context of human-robot interactions (HRI), there is limited knowledge on whether these findings can be applied to human-drone interactions (HDI). Flying robots introduce a novel interaction paradigm, and early research indicates that insights from HRI with ground-based robots do not readily or directly transfer to HDI. Some researchers have questioned the relevance of using Hall's framework in HDI, as it assumes that people's behaviors around drones are socially driven, treating drones as social actors akin to humans. However, given the mechanical nature of current drones, this assumption may not hold. To address this uncertainty and assess the pertinence of Hall's framework, we devised a user study where participants naturally navigate around a drone under various conditions known to influence proxemics among humans and humanoid robots. Our aim is to compare the results to expectations based on drones being perceived as social entities, or to identify other mechanisms at play.

Drones possess a unique characteristic that sets them apart from humans and ground-based robots: their ability to fly. Since most casual encounters with drones will occur while they are in the air, we investigate how the drone's flying height affects people's proxemic behaviors.

- **RQ1:** How does the flying altitude of an autonomous drone affect individuals' proxemic behaviors?

If drones are perceived as social entities, a "taller" drone (one flying at a greater altitude) would be seen as more dominant, similar to social dynamics among humans, leading people to maintain greater distances [342].

Additionally, given the novelty of this technology, people's perceptions can be strongly influenced by how the drone is presented.

- **RQ2:** How does a positive social framing influence individuals' proxemic behaviors compared to a technical framing?

If drones are perceived as social entities, improving people's perception of them before interaction should result in closer interaction distances. We explore whether proxemic preferences can be altered through framing techniques.

Study Design & Methodology We conducted a proxemic user study (N=45) in virtual reality, focusing on (1) the impact of the drone's flying height and (2) the type of cover story used to introduce the drone (framing) on participants' proxemic preferences.

Results Our findings show that drone height significantly impacts participants' preferred interpersonal distance, but not as hypothesized from a social perspective. Framing had no significant effect within the specific context of our study, despite initially promoting a more positive social perception. Participant feedback provided a nuanced understanding of the results, highlighting unmet expectations and potential biases related to their backgrounds. Additionally, participants' thoughts on social drones (e.g., interaction, design, applications) revealed many interpersonal differences but also showed overall consistency over time. The results indicate that, due to their current mechanical design, drones are not perceived as social entities, and people's proxemic behaviors around drones are not socially driven. This motivated Study #2, which investigates the proxemic influence of social cues for drones. Additionally, researchers can use Virtual Reality (VR) for such experiments, but further research is needed to determine how these findings translate to real-world settings. This led to the development of a real-world/VR comparison study, which is presented in Chapter 4.

3.2.2 Related Work

This section synthesizes related work on the specific topics addressed in this study, including the drone's flying altitude and framing in HDI. A detailed literature review of proxemics and virtual reality can be found in chapter 2.

Flying Altitude

Duncan et al. and Han et al. [107] examined the impact of a drone's altitude on preferred distance but found no significant effect when comparing high (2.13m) versus low (1.52m) hovering heights or above-the-head (2.6m) versus eye-level (1.7m) drone heights [164]. Although they did not observe any effect of drone height on comfortable distance, their methods of ensuring safety during the experiments raise questions about the ecological validity of their results, as pointed out by the authors themselves [107]. We believe that explicitly controlling and limiting the settings may impact how participants perceive the situation (such as their perception of threat) and their ability to exhibit natural behaviors, potentially leading to biased proxemic observations. To address these concerns, we have opted to use of virtual reality (VR) as a testbed. By doing so, we hope to provide a controlled and safe environment that enables us to investigate HDI proxemics with a high degree of ecological validity. A detailed literature review of Proxemics and Virtual Reality is presented in chapter 2. Additionally, a paragraph addressing the validity of VR for this study is included in the methodology section.

Framing

Theoretical Background Apart from investigating the impact of drone height on participants' proxemic behavior, we also examined the influence of framing on their behavior around the drone. Frames are structures that can increase or decrease the relevance of different aspects of a situation [37]. The process of creating a frame, known as framing, involves the selection and emphasis of specific information [117]. For example, when communicating about a topic, such as a situation, object, or person, choosing to highlight or omit particular information can shape how it is perceived. The framing process can be influenced by existing individual frames, as highlighted by [312]. This means that hidden information can be brought to the forefront, while highlighted elements may be minimized, and a discrepancy between the individual's own frames and the produced frames can lead to resistance to the framing [117]. Ultimately, the framing effect can be negated or even have the opposite effect [37]. Furthermore, produced frames are more likely to be resistant when they are presented to individuals with a medium-level knowledge of the topic [225].

Framing for HDI Therefore, it is crucial to investigate how framing affects the way people interact with drones, especially during the early stages of human-drone interaction (HDI), to ensure their successful integration into society. Currently, only a small fraction of people have had many experiences with drones, and the general frame that most people hold about drones is characterized by their fragility, instability, and unpredictability. Additionally, people with limited knowledge are more susceptible to the impact of new information (or frames) [225]. As a result, a person who has only heard about drones through news reports of accidents is likely to be wary of their potential dangers when encountering a drone for the first time.

Studies have repeatedly demonstrated the use of framing effects to manipulate people's initial reactions to robots, including influencing perceptions of their social or human-like qualities [91, 95, 180, 209]. By highlighting specific dimensions of the drone, we could potentially achieve our goals, such as reassuring an injured person during a rescue operation. Therefore, it is crucial to consider the potential biases introduced by framing in research involving drones. For instance, Chang et al. [82] framed drones as a potential threat to privacy before assessing participants' concerns about them. As a result, the experimenters found more negative aspects of drones than positives, which contrasts with findings in prior works. This suggests that framing can unintentionally bias the results of an experiment if not carefully considered. Previous studies have investigated the framing effect in some human-robot interaction research [35–37, 95, 110, 129, 304]. However, its application in HDI has received relatively little attention [172, 174]. Therefore, our work has the potential to provide valuable insights to companies, public services, and other stakeholders on how to present their drones in a way that promotes a positive user perception when deployed in public spaces.

3.2.3 Methodology

In this experiment, we study how the framing effect and drone's flying height influence participants' proxemic behavior in an immersive virtual environment (IVE). The process of distancing from one another is not a thoughtful and reasonable decision, but rather an automatic instinctive response in reaction to multiple sensory inputs [163]. Instead of the typical stop-approach procedure often used for Human—Drone Proxemic studies (see [107, 230]), we opted for a more natural approach to observe participants' proxemic behaviours. As seen in [31, 263], we observed participants' proxemic behavior while they performed a task (interactional method, see section 2.2) that required them to pass by a flying drone in the virtual environment (see Figure 3.1). To precisely measure the distance between participants and the drone, we recorded their movements using the VR headset's position in the IVE. All manipulations, measures, sample size justification, and main hypotheses were pre-registered on the Open Science Framework (OSF) before data collection: https://osf.io/7a4xu. We report all manipulations and measures in the study, in line with recent proposals [138].

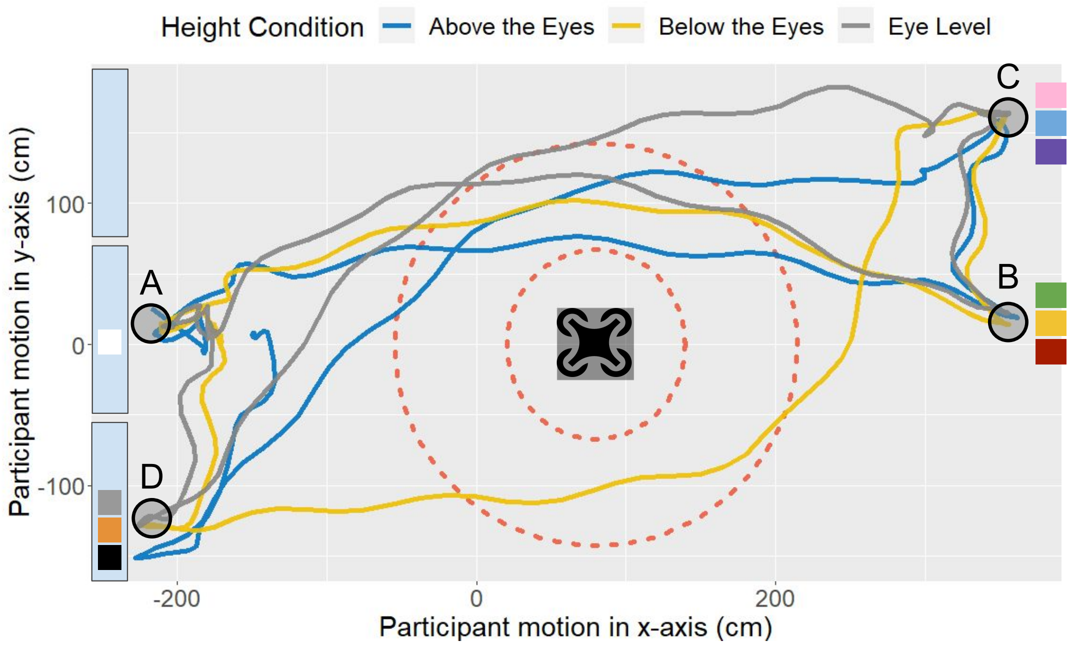


Figure 3.1: Top view of a participant's path as they walk from the starting point (A) around the virtual drone to reach the colored papers (B,C,D) in the room. The sequence of colors to reach appears on the paper (white square) located on the table (blue rectangle) next to the initial position. The circular boundaries around the drone correspond to Hall's framework's intimate and personal spheres, respectively. We notice that the participant follow similar paths but maintain different distances between the conditions.

Experimental Design

The experiment follows a 2 x 3 mixed design. The independent variable, *Framing*, is a between-participants factor and has two levels: *social* and *technical*. The participants are assigned to either the social or technical framing group, and read a different presentation about the drone before the task. To induce a social framing of the drone, the social-oriented framing text uses a pet metaphor, assigns a name to the drone, and describes social applications. Some individuals tend to perceive autonomous drones as similar to pets [76]. We chose the pet metaphor to revive this phenomenon and evoke a stronger emotional connection compared to perceiving the drone as a mere object. Additionally, using a pet metaphor, as opposed to a human metaphor, helps mitigate potential social anxieties that can sometimes arise in human social interactions [269]. In contrast, the technical-oriented presentation is purely descriptive, using technical terms only (see Appendix section A) while matching the social framing text in other surface features. The participants' perception of the drone before their first encounter was evaluated through the Robot Social attribute Scale (RoSAS) [74] and post-experiment interviews.

The independent variable *flying height* is a within-participants factor and has three levels: *above the eyes* (1.95m), *eye-level* (1.5m), and *below the eyes* (1m). Previous experiments have explored various categorical levels associated with fixed drone heights such as tall, short, overhead, and eye level [107,164,389]. In this experiment, we defined the drone as being at eye level when it was between +/-15cm relative to the participant's eye height. The maximum height of the drone was limited to 1.95m due to the dimensions of the room. The height conditions' order has been randomized using a Latin square [154]. The data collected during the study and used in the analysis are presented below.

Proxemic Measure The dependent variable used as a proxemic index is the minimum distance measured between the participant and the drone for each condition. Minimum distance is a crucial indicator of personal space boundaries, which define the limits beyond which individuals may experience anxiety, discomfort, or stress. This metric is a widely accepted and standardized metric in proxemic research. Its consistent use across studies allows for meaningful comparisons and facilitates the integration of our findings with existing literature. In contrast, average distance can be less informative in this context due to its susceptibility to task-related variations. For instance, participants may take extra time to identify a target paper or observe the drone from a distance before approaching closely. These variations can lead to higher average distance values, even when the maintained distance is actually small. Therefore, using minimum distance measures is more appropriate for accurately capturing proxemic behaviors in this study. To measure this distance, we use the position of the participant's head (as indicated by the VR headset) relative to the drone in the virtual environment. This method is similar to that used by Baileson et al. [31]. The system records the participant-drone distance at a fixed frequency of 5 Hz, which enables us to visualize the paths taken by the participants during the task (as shown in Figure 3.1).

Semi-Directed Interview After the completion of the experiment, we conducted semi-directed interviews (30-45 minutes) with the participants to gain insights into their perception of the drone during the task, the effect of the presentations, their experience in the virtual environment, and their perspective on the future of personal drones. The interview guide sheet, which includes questions posed for each theme, can be found in the appendix (see Appendix section A). We used an affinity diagram to identify and organize the themes that emerged from participants' responses in the post-experiment interviews. An affinity diagram is a method used to organize large amounts of data, such as the responses gathered in the semi-directed interviews, into meaningful themes or categories [245]. The researchers started by familiarizing themselves with the data during the transcription process. Following that, an initial inductive examination of the data was carried out, involving the assignment of codes to significant and relevant concepts. These individual ideas were documented on digital sticky notes displayed on a virtual whiteboard. Ultimately, axial coding was employed to establish categories and uncover connections among the codes.

Presence Questionnaire In addition to the post-experiment interview, we used the Igroup Presence Questionnaire (IPQ) [315] to evaluate participants' level of presence. This was important because how physically present people feel in the simulation can have a significant impact on their experience [69, 101]. However, even if we try to maximize the presence with high immersion (see section 2.3), we cannot assume that it will always be effective. The degree of presence depends not only on the environment's characteristics but also on the individual's cognitive characteristics, such as their mental imagery ability [184] or personality [99].

Setup and Apparatus

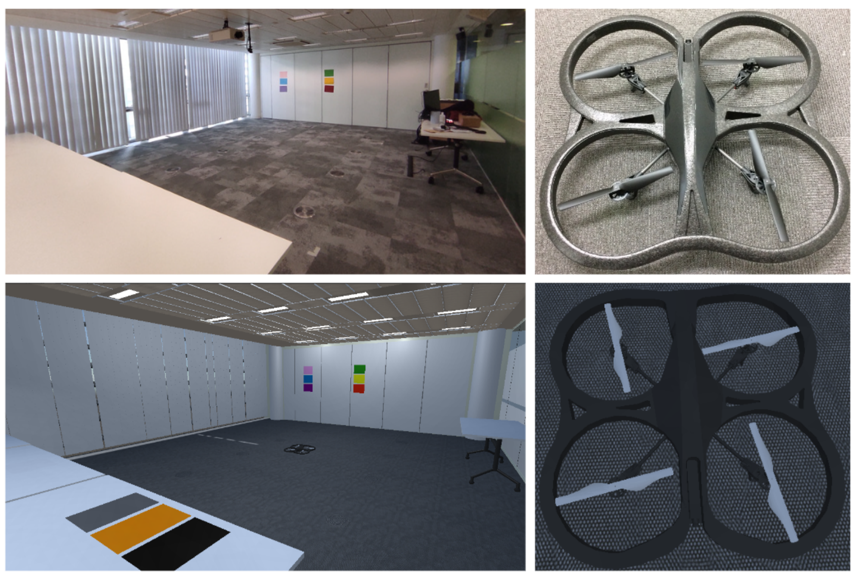


Figure 3.2: The experimental room and the real Parrot AR.Drone 2.0 (top) next to their virtual replica (bottom) in Unity 3D. Participants' paths were recorded in the simulation (see Figure 3.1), allowing the accurate assessment of proxemic preferences around the drone, in a safe and realistic environment.

This study employs the experimental setup described in section 2.3.2. Participants wore a Meta Quest 2 and navigated around a stationary hovering drone to reach specific areas within the virtual space (see Figure 3.2). Participants had their hands free and could see them in the simulation without using controllers. The Unity project is available on the Thesis GitHub repository [56].

Drone Design The virtual drone, a Parrot AR 2.0 (see Figure 3.2), was controlled through a C# script with predefined animations to ensure high replicability. The experimenter used a VR controller to run the animations in response to the participant's voice commands, following a Wizard of Oz approach. While we aimed for consistency in the drone's response time throughout the study (0.5 to 1 second), some variability was inevitable. The virtual drone's behavior was intended to replicate that of a real drone, and spatial audio was added to simulate the sound of the drone flying and landing in VR.

Ecological Validity The general challenges associated with using VR for proxemic studies (i.e. motor abilities, distance compression), along with the solutions implemented in our experimental setup, are discussed in section 2.3.2.

Participants

Before the experiment, participants filled out a questionnaire to provide their demographic information, prior experience with drones or virtual reality, adjectives they would use to describe drones, and their knowledge of drone applications (see Appendix section A). A total of 45 participants (27 male, 17 female, one non-binary), mainly from scientific backgrounds such as computing science, psychology, and veterinary, were recruited. The participants were between 17 to 38 years old, with various levels of experience with drones and VR, and from different origins. The distribution of origins by region is as follows: Europe (23), Asia Pacific (13), Latin America (2), Middle East (6), Africa (1). Regarding experience with virtual reality (VR), 11 participants had no experience, 21 had a little experience, 6 had good experience, and 7 had a lot of experience. As for drones, 5 participants had no experience, 27 had a little experience, 12 had good experience, and 1 had a lot of experience. The average eye height of the participants was measured using the average headset height during the simulation (M=155cm, SD=9.5cm, range=136.4cm-174.5cm). To ensure gender parity and equal group sizes, participants were randomly assigned to either the social or technical group. The research received ethical approval from the University of Glasgow Ethics Committee (reference number: 300210015).

Protocol

The experiment began with participants being welcomed to the experimental room, where they filled in the consent form and were informed that the room had been replicated in VR. Next, participants read a short cover story (see Appendix section A) that introduced them to the drone they would be interacting with. Participants then completed the RoSAS questionnaire [74] to assess their initial perception of the drone. Next, they were given the experimental protocol to read (see Appendix section A) before putting on the Meta Quest 2 headset and being immersed in the virtual room.

Once in the virtual room, participants were instructed to ask the drone to search for their keys by saying either “Drone, look for my keys" or “Happy, look for my keys", depending on the framing. The drone then took off and a sequence of three colors appeared on the table next to the participant (see Figure 3.1). Participants had to memorize the sequence, touch the colored papers in the same order, and then return to the initial position. The drone was then instructed to land by saying “Happy, land" or “Drone, land." During the participants’ movements, the drone remained stationary, hovering in place as if it were scanning the room while simulating occasional shakes and subtle movements, similar to what one might observe in real hovering drones. This procedure was repeated three times, with different color sequences and height conditions. The initial position, paper locations, and arrangements were designed to force participants to pass by the drone from the front and diagonally for each height condition.

After completing the experiment, participants filled out the IPQ questionnaire [315] to assess their perceived sense of presence. Finally, a semi-directed interview was conducted (30-45 minutes).

3.2.4 Quantitative Results

This experiment aims to explore participants’ proxemic preferences and perception of social drones by investigating the effects of flying height and framing, while also contributing to the development of virtual reality as a tool for human-drone interaction studies.

Table 3.1: Results of the Bonferroni-corrected multiple paired t-tests for each height condition. All pairwise comparisons are significant.

group1	group2	n1	n2	statistic	df	p.adj	p.adj.signif	Cohen’s d
Above_Eyes	Below_Eyes	45	45	-5.1	44.0	0.00002	****	-0.5956
Above_Eyes	Eye_Level	45	45	-2.9	44.0	0.02000	*	-0.3095
Below_Eyes	Eye_Level	45	45	3.0	44.0	0.01300	*	0.3137

We conducted a mixed ANOVA with one between-participants factor (Framing) having two levels and one within-participant factor (Height) having three levels (2b*3w). The dependent variable was the minimum distance between the participant and the drone for each set of conditions. We checked for normality (Shapiro-Wilk test, $p > 0.05$) and homogeneity of variances (Levene’s test, $p > 0.05$) and covariances (Box’s test of equality of covariance matrices, $p > 0.001$). Our test also checked the sphericity assumption (Mauchly’s test) and applied the Greenhouse-Geisser sphericity correction to factors violating the assumption. The results showed a significant main effect of Height ($F(2,86) = 14.948$, $p = 2.68e\text{-}06 < 0.0001$, ges=0.062), but no significant effect of Framing and no interaction between the two variables.

Height Regarding the Height factor, multiple pairwise paired t-tests with Bonferroni correction revealed significant differences between each height condition (see Table 3.1 and Fig-

Figure 3.3: **A.** Effect of the *Height* on the distance for each *Framing* condition. The boxplot indicates a significant decrease in the minimum maintained distance when comparing Above_eyes with Eye_level and Below_eye, and Eye_level with Below_eyes. **B.** Effect of the *Framing* on each RoSAS factors. We found a statistically significant higher warmth score for the *Social* condition and no significant difference for the competence and discomfort factors.

ure 3.3). Participants were significantly closer to the drone in the Above Eyes condition (M=92.6cm, SD=44.8cm) compared to the Below Eyes condition (M=114.7cm, SD=27.5cm) ($p<0.0001$), the Above Eyes condition and the Eye Level condition (M=105cm, SD =34.4cm) ($p<0.05$), and the Below Eyes condition and the Eye Level condition ($p<0.05$). The findings indicate that participants tended to approach the drone when it was above their eye level and maintain a greater distance when it was below their eye level compared to the other two conditions.

Framing In order to evaluate the impact of Framing on participants' perception of the drone prior to their initial interaction, we utilized the RoSAS [74]. This survey consists of 18 items, which are divided into three factors: warmth, competence, and discomfort. The score for each factor is calculated as the mean of the scores for its associated items. For each of these constructs, we conducted a Welch two-sample t-test, which revealed a significant difference in the Warmth ($t(41.14) = 3.4938$, $p < 0.005$, $d = 1.030259$) rating (see Figure 3.3). Participants' feedback during the post-experiment interview supported this result, indicating that we effectively emphasized the social aspect of the drone. We hypothesized that participants would maintain a smaller distance from “Happy" due to the drone's socially-framed appearance, however, we found the opposite to be true. On average, the social group kept a greater distance (M=111.3 cm, SD=41 cm) than the technical group (M=96.6 cm, SD=31.1 cm). This difference was not statistically significant, and as a result, we cannot generalize this finding. This observation is intriguing and warrants further exploration.

Presence Participants' presence in the virtual environment was evaluated using the Igroup Presence Questionnaire, which includes items divided into four factors: general presence, involvement, realism, and spatial presence. The mean scores of each factor were used for analysis. Results showed that participants had a relatively high overall presence in the virtual environment, as indicated by positive scores for each dimension (see Figure 3.4). This suggests that the virtual environment was sufficiently convincing to elicit natural behaviors from most participants, which was also supported by feedback received during the post-experiment interview (see section 3.2.5).

Summary

- **"Taller" Drone Does Not Lead to Greater Distance:** Participants tended to approach the drone significantly closer when it was positioned above their eye level (M=92.6 cm, SD=44.8 cm) and maintained a greater distance when it was below their eye level (M=114.7 cm, SD=27.5 cm) compared to the eye-level condition (M=105 cm, SD=34.4 cm). These findings contradict the expectation that a taller drone would result in a greater maintained distance, as observed with humans and ground robots. This discrepancy suggests a shift in the underlying mechanisms driving proxemic behaviors, as discussed in subsection 3.2.6.

- **Social Framing Enhances Initial Perception but Does Not Decrease Proxemic Distances:** On average, participants in the social framing group maintained a greater distance (M=111.3 cm, SD=41 cm) compared to those in the technical framing group (M=96.6 cm, SD=31.1 cm), though this difference was not statistically significant. While the social framing effectively enhanced participants' social perception of the drone before the interaction, it did not result in reduced distances during the task. This suggests that social framing did not influence the proxemic behaviors of participants, indicating that other non social factors may be driving the distances maintained around the drone. This result is further clarified by the qualitative findings presented later.

- **Validity of the Immersive Virtual Environment (IVE):** Results showed that participants experienced a high level of overall presence in the virtual environment, as reflected in positive scores across all dimensions (see Figure 3.4). This indicates that the virtual environment was sufficiently convincing to elicit natural behaviors from most participants. This conclusion is further supported by feedback obtained during the post-experiment interviews (see section 3.2.5).

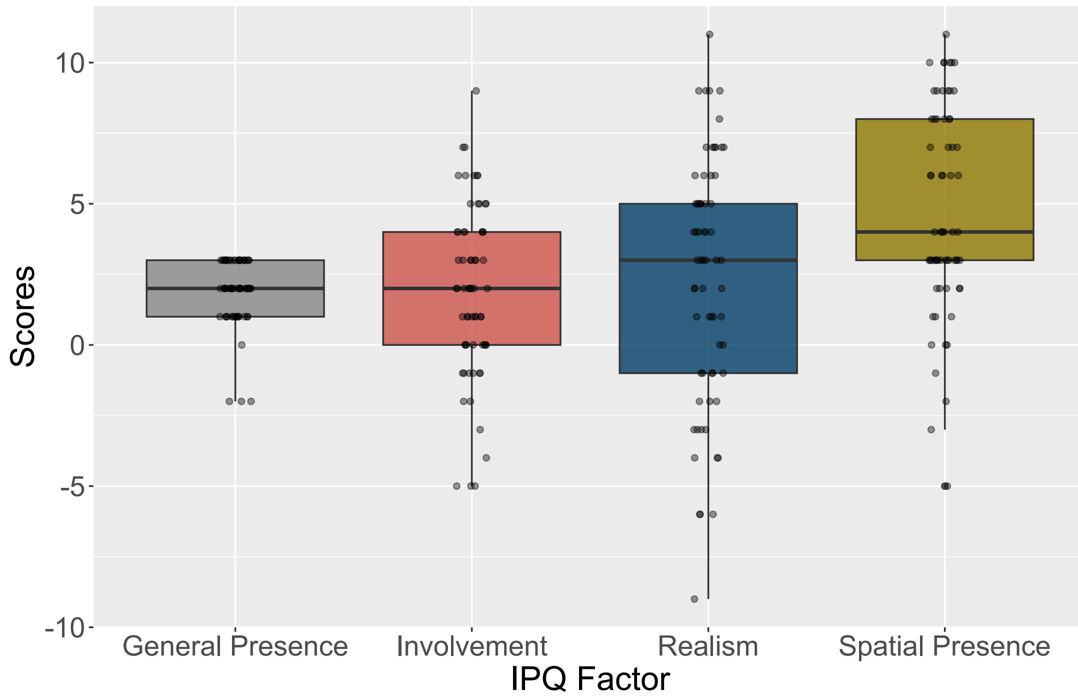


Figure 3.4: Boxplot of the IPQ results for each dimension. Each mean is positive suggesting a relatively high overall presence: M(General Presence)=1.92, M(Spatial Presence)=4.74, M(Involvment)=1.86, M(Realism)=2.3

3.2.5 Qualitative Results

After completing the experiment, we conducted semi-structured interviews (see Appendix section A) with participants to explore their perceptions of the drone during the task, the influence of the presentations, their virtual environment experience, and their expectations for the future of personal drones. We used an affinity diagram technique to identify patterns and themes in the participants' feedback [245]. We assigned a distinct code to every idea within the responses provided by each participant for each question. These distinct ideas were documented on digital sticky notes and displayed on a virtual whiteboard. In the final step, we utilized axial coding to create categories and reveal relationships among these codes. For questions where it was applicable, such as "How would you interact with it?", this approach also allowed us to quantify the size (number of occurrences among participants) of the resulting categories and visually represent these results as shown in Figure 3.7. The specific questions from which the responses come from are provided in the figures' caption. It's important to note that due to the semi-directed nature of the interviews, not all questions from the guide sheet (Appendix section A) were posed to each participant, and participants could provide multiple responses, leading to variations in response frequency.

Based on the resulting affinity diagram, we report the primary themes. Participants' responses are identified with (P+participant ID).

Co-existing With a Drone

We investigated participants' perception of the drone while performing the task and gathered their opinions on both the social and technical presentations.

Where Was Your Attention Focused? During the interviews, participants were asked about their focus during the experiment. The majority of them reported that they were primarily **focused on performing the task** at hand. For instance, one participant mentioned that they did not pay much attention to the drone as they were more concerned with completing the task correctly. (P30) said “I was more focused on doing the task. I didn't really pay much attention to the drone". Some participants **shared their attention between the task and the drone**, with some reporting that they used their listening senses to monitor the drone while visually focusing on the task. (P38) said, “Basically I think that through listening I can be more aware of if the drone is a threat to me. But visually I was more focused on finding the colors". However, a minority of participants reported that they were **focused on the drone itself**, with one participant noting that they constantly looked at the drone because they thought it would move.

Moving Around the Drone Participants had diverse feelings and perceptions during the phase where they had to move around the drone to reach the colors. Some participants expressed concern about **interfering with the drone's task** or damaging it. For instance, participant (P2) said, “I don't want to ruin it because it looks real", and participant (P24) was worried that they might “affect its function." In contrast, others perceived the drone as a **real object** and were careful to **avoid it to stay safe**. Participant (P35) stated that they felt fearful because of the mechanics working, and the drone was at their level. Some participants were **distracted by their task and ignored the drone**. For example, P31 tried to “just ignore it," and (P29) was focused on their task and said that “even if it was real, I think I wouldn't think too much about it." Meanwhile, others were **curious** about the drone's behavior when approached. Participant (P20) expressed their curiosity, saying, “I wanted to see if it responds to anything else," and (P8) “wanted to kind of challenge it." Additionally, some participants were motivated to avoid the drone due to the **noise** it made. (P17) said “the noise felt so real and I was like whoa no no", and (P13) moved due to “the fear induced by the loud sound of the propellers".

What Did You Think of the Drone? The participants expressed their thoughts on the drone and suggested some changes they would like to see. They found it “**a bit big**" (P25) for an internal drone and recommended reducing its size to make navigation easier in “confined spaces" (P16). The sound of the drone was also a concern, as it was considered “**quite loud**" (P21) and similar to that of an insect (P18). Some participants suggested a “nicer noise" (P36), while others proposed making it “less noisy" (P28) to avoid distraction. However, the drone's sound was also noted to serve as a location cue. (P28) added that “you don't want it to be completely silent in case you walk into it" and (P14) said, “the good part is that with the noise [...] you are a bit more aware that it’s there". To address concerns about its **unfriendly appearance**, some participants recommended adding social features such as a “smiley face" (P18) or animal-like shapes like “a butterfly or something cute" (P14). Participants also mentioned a **gap between their expectations and the actual appearance of the drone**. (P35) said, “when I was reading the description, it seemed to be, oh, it’s such a sweet drone you know. [...] But it’s very impersonal [...] It was very straight lines, you know, and being all black". Similarly, (P7) “didn’t really get a social feeling from it" and (P31) explained, “I thought it would be smaller than that, and probably not black, then something that looks quite friendly and cute or something. So I was kind of surprised there was like a large black generic looking drone". Some suggested the use of “more warm colors" and making it “less rough" (P35). Other requested **functionalities** include indicating the direction of its sensors (P22) and automatic collision detection and avoidance (P0).

Social Expectations During the study, two different presentations were shown to the participants. One of them was socially oriented, while the other was neutral and focused solely on presenting the technical aspects of the drone (see Appendix section A). In the interviews, participants were shown the other presentation and asked if they thought their behavior or perception of the drone would have been different if they had seen that presentation instead.

Some participants stated that the social presentation would not make a difference for them, as they were **not sensitive to social cues** and preferred the technical presentation due to their specific **interest in technology**. (P25) said “I would be able to, you know, control my natural instincts as human and look at it objectively". Yet (P9) expressed the belief that they are part of a minority “when it comes to how interested I am in drones", and therefore preferred not to have a technical presentation because it would make the drones seem less human for others. This perspective is in line with other participants who noted a **positive perception of the social presentation** compared to the technical one. According to (P9), the social presentation is beneficial for end-users because it can improve their negative overall perception of drones. Similarly, (P29) believes that the social presentation is more positive and less intimidating, making people more open-minded about drones. (P2) suggests that the social presentation may make drones more acceptable to people who are hesitant to interact with technology. The way the drone was presented socially appears to have influenced how participants perceived the **drone’s social role**. For example, (P3) suggested that naming the drone would make it feel like a pet, while (P16) thought that it could be a replacement for a deceased animal. (P5) also believed that a social presentation would give the drone more character and make it feel like a companion, rather than just an object. These social roles influenced participants’ behavior towards the drone, with (P23) saying that they would have paid more attention to the drone if it had been presented socially, and (P5) indicating that they only walked around the drone but would have acknowledged it more if it had been presented as a companion. A group of participants expressed their feelings of **dissonance** between the social presentation and the actual drone. For instance, (P38) mentioned that while the social presentation made the drone seem friendly, the actual drone might still appear as a tool, which creates a discrepancy between expectation and reality. Similarly, (P18) felt that the actual drone did not match their expectations based on the social presentation, creating a significant difference that they could not explain. (P29) also mentioned that the social presentation made the drone more engaging and personable, but they did not have the same feeling when interacting with the actual drone. (P35) pointed out that the social presentation induced positive expectations and feelings, but they experienced disconnection and dissonance when interacting with the actual drone. (P35) said "If the presentation was different, like just objective and technical, I would go there without any expectation like this is going to be a drone. [...] It's funny because, since I had such a dissonance because you are inducing these feelings it's going to be something sweet. So before interacting with the drone, in my head I was not visualizing the drone itself. It was just a blank. So there was some disconnection between what I saw and what I thought I would see. So you just change this first part here. Being more technical, yeah, it's totally different. My expectations would be totally different. When I started the experiment I had like a positive expectation. How could I expect a drone to be friendly or empathetic? I could not even visualize the drone in my head." Overall, the significantly higher perceived warmth for the social presentation before interacting with the drone underscores the expectation difference between the two presentations (see Figure 3.3).

Experimenting in VR

During the interviews, we also investigated participants' feelings while navigating the virtual environment, with the aim of identifying any potential constraints of using this approach for future HDI proxemics research, gaining a deeper insight into the subjective impacts reported by participants as well as to gather ideas for improvements.

A Compelling Virtual Experience According to participants' feedback, the virtual environment (VE) was perceived as convincing and realistic, which is consistent with the results of the presence questionnaire (see Figure 3.4). Specifically, the virtual replica of the room and the drone's aspect, sound, and behavior were mentioned as crucial elements for their immersion. Many participants described the VE as "realistic and accurate", such as (P3) who felt that "it felt completely real", (P7) who noticed "barely any difference", and (P31) who reported that "it's almost like you're not putting anything on" when wearing the goggles. Some participants also emphasized the importance of the drone's realism, such as (P1), who appreciated that "it looked like a drone that I'd seen before and the sound was very realistic to a drone flying and its movement". (P33) also felt that "the simulation really gave that experience of having a drone in the room", and even felt cautious with the drone's presence, despite knowing that it was only a simulation.

However, some participants also mentioned certain issues that hindered their immersion in the VE. For instance, P20 felt that the VE was “too clean", while P4 reported that “the frame rate was quite low", and P29 mentioned that “the resolution was off". These issues align with the participants’ suggestions to improve the VE further (see Figure 3.5).

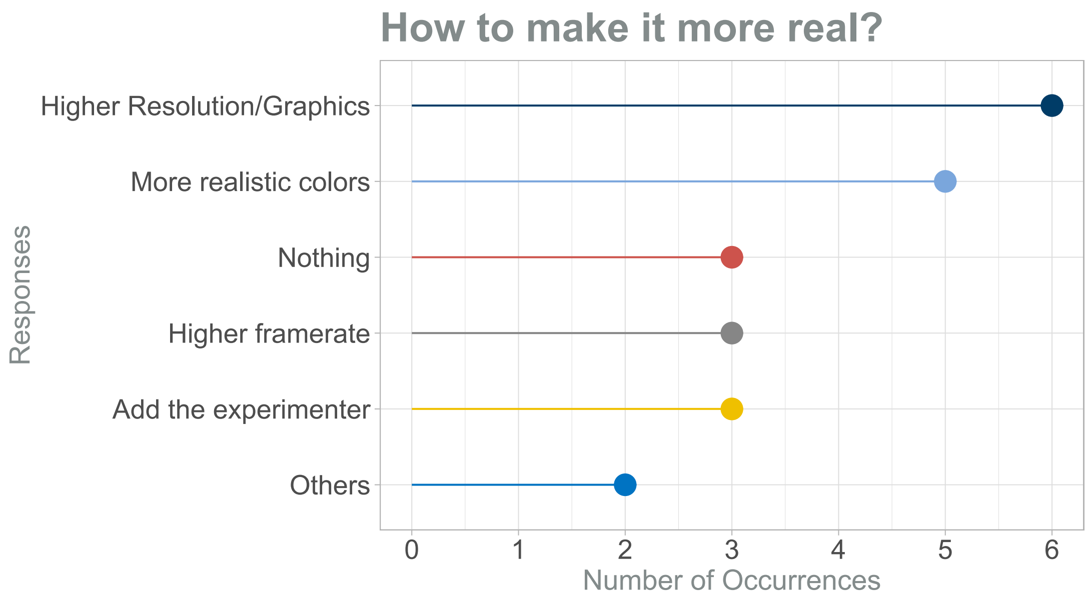


Figure 3.5: Responses to the question “Compared to a real-world environment, what do you think was missing to make it more compelling?" and their frequency. Its technical performances (resolution, frame rate) and visual aspect were the principal ways of improvement.

Difference With the Real World We inquired whether participants would have acted similarly if the experiment had taken place in the physical world. The majority of those who answered would have either acted the same (n=21) or kept a greater distance (n=9). For instance, (P35) cited the noise and said, “If the drone made the same noise and was just as annoying, I would behave the same way." (P7) mentioned safety, stating that “even though it was a virtual drone, I would not really go near to it. Just to be scared if it cuts my ear or something." (P18) supported this perspective by commenting, “Oh, I totally put myself in the environment, and I totally thought that if it flew towards me, I would duck. I would like run away." Interestingly, contrary feedback has been given. (P38) remarked, “I felt safe. It can’t literally hurt me, but if it’s a real one, I think I would want to keep a safer distance from it," and (P3) stated, “I would have probably given it more distance because I thought you know that could really harm me." These findings indicate that changes in threat perception can occur in virtual reality and may be influenced by individual factors.

Future of Drones

During the interviews, we prompted participants to imagine a hypothetical scenario where drones were widely used and had no technological limitations, and they themselves had a personal drone. Within this context, we asked participants to share their opinions on potential applications, methods of interaction, reasons for potential rejection, social acceptability, and how their personal drone would differ from public or company-owned drones.

Applications As presented in Figure 3.6, participants predominantly mentioned using their personal drone to assist with **household tasks** such as “cleaning the house" (P31), “walking the dog" (P24), or “tidying up the room" (P9). The next most frequently reported uses were **photography**, **transporting or delivering objects**, and **surveillance**. These applications align with the existing known uses of drones as reported in the demographic questionnaire (see Appendix section A). Some participants expressed a desire for the drone to be a **companion** or to accompany them while jogging ((P9) “having a drone to go with me would encourage me more."). Lastly, participants mentioned using their drone as a remote pair of eyes to **monitor specific areas** (e.g., (P4) “I want to go play basketball and I'm not sure how many people are there.", (P20) “check where there is traffic.").

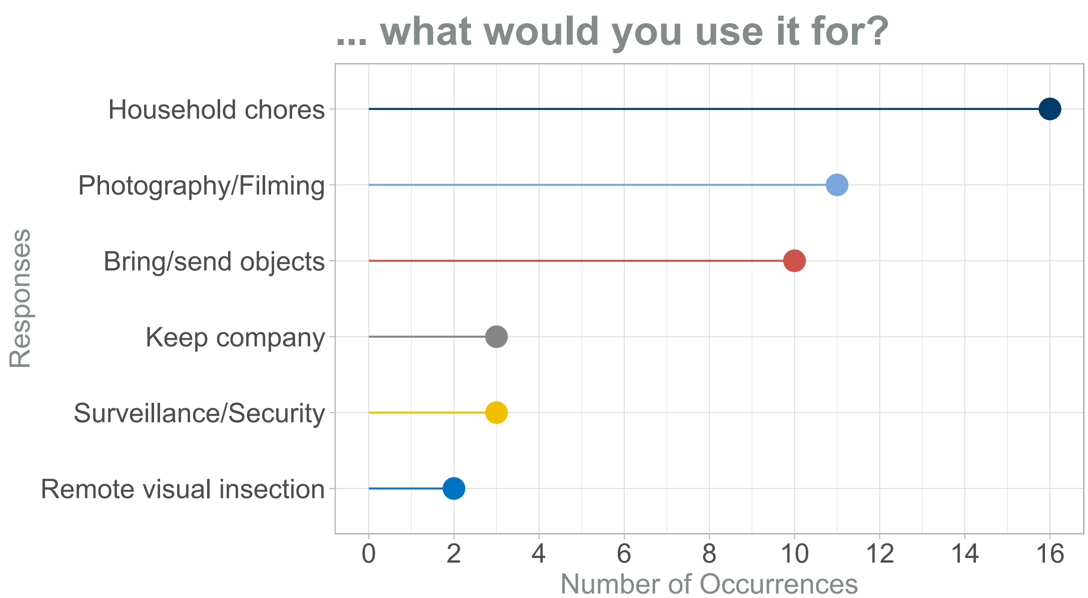


Figure 3.6: Categorized responses to the question “If you had a personal autonomous drone, what would you use it for?" and their frequency. The most mentioned application is to help with household chores (i.e., cleaning, tidying, shopping, and taking care of animals).

Mode of Interaction Participants were asked about their preferred modes of interaction with their personal drone (see Figure 3.7). The majority of participants mentioned using **vocal commands** or speaking to the drone naturally. Some participants also mentioned using an **interface screen** such as an app or computer, or incorporating **gestures** or body language along with vocal commands. Interestingly, a few participants mentioned the possibility of using a **brain-computer interface** as the ultimate mode of interaction. For example, one participant (P7) stated, “If there’s anything better than voice, then I guess it’s neural signals".

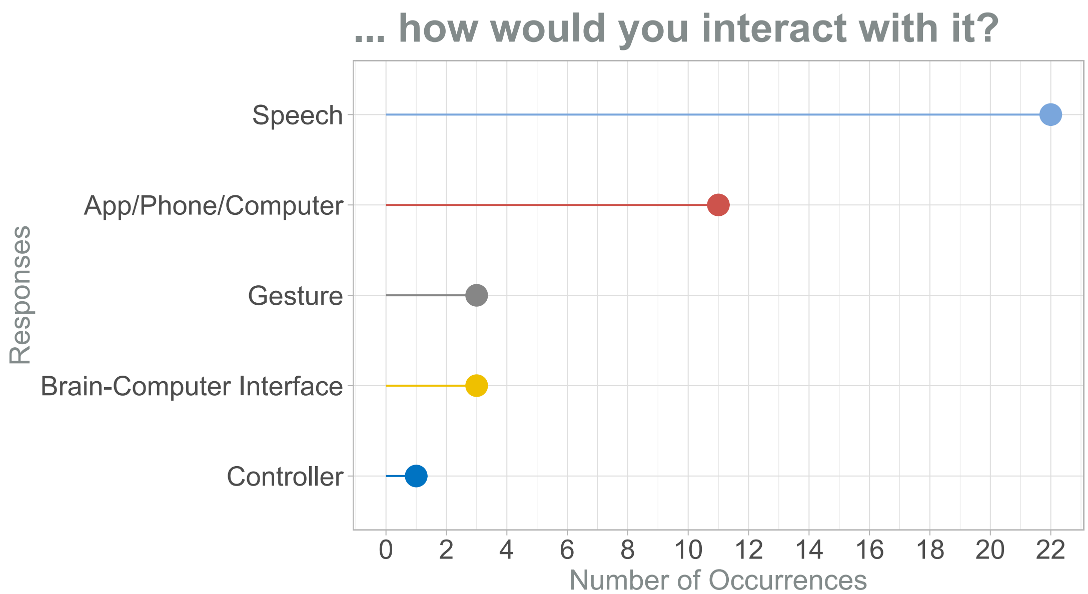


Figure 3.7: Categorized responses to the question “How would you interact with it?" and their frequency. Most participants preferred speech interaction alone or in combination with other modes (i.e., non-verbal communication or screen interface).

Reasons for Drone’s Rejection: *Performance, Safety, Privacy, and Design Concerns* Participants cited several reasons why they would stop using their drone. The primary reason was the drone’s **performance**, such as unresponsiveness, unreliability, and inability to avoid collisions (e.g., (P24) “If it does not do what I’m saying", (P36) “If I had to say commands like quite a few times. Or if it did the wrong thing.", (P18) “If it bumps too much into things"). Participants also expressed concern about the drone’s **safety**, such as causing harm to people or damaging property. **Privacy and data usage** were also important factors for rejection, as some participants worried that their actions and conversations might be recorded and shared without their consent. Design characteristics, such as noise level and bulkiness, were also mentioned as potential reasons for rejection. Finally, some participants mentioned rejecting the drone for **other reasons**, such as difficulty in interacting with it, poor company updates, or having to pay a monthly fee to use it.

Social Acceptability We asked participants how they would feel about using their drones around unfamiliar people. Some expressed concern about how others would perceive it, with one participant noting that it “**depends how socially acceptable it is**" (P38). Most participants said they would feel uncomfortable using their drones around strangers at this stage, but they believed this feeling would change as drones become more common. Others said they would

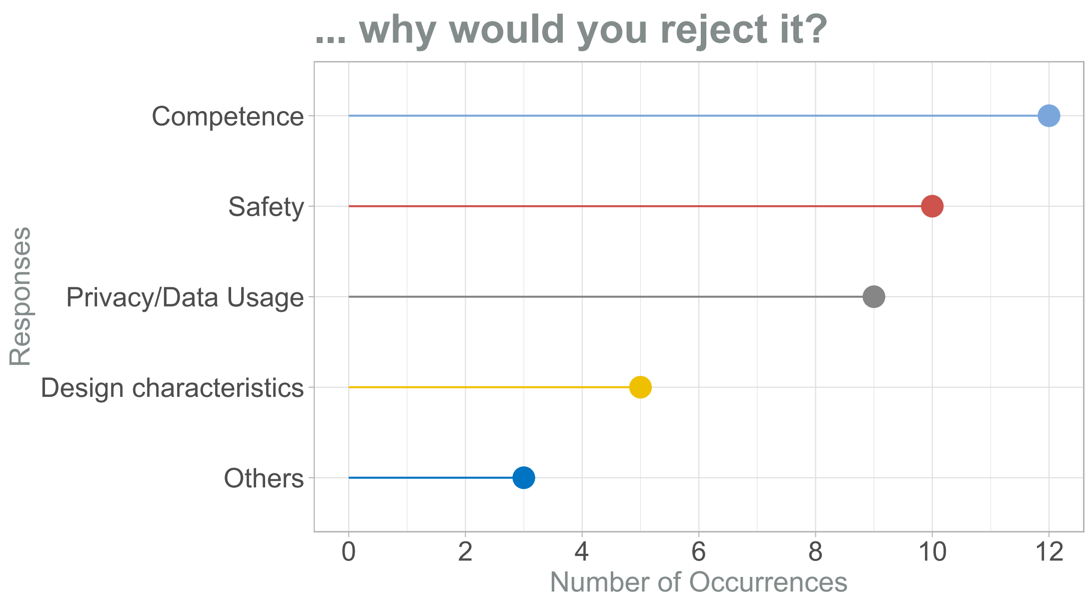


Figure 3.8: Categorized responses to the question “Why would you reject the drone?" and their frequency. The inability to meet expectations in terms of performance was the first reason to reject the drone, followed by safety and privacy concerns.

not care either way. (P26) and (P18) said respectively they “**would not care**" if “I’m the only one" or “if they’re annoyed".

When we asked participants how they would feel if someone else was using a drone near them, their responses fell into three categories: negative perception, neutral or positive, and context-dependent. **Negative perceptions** were mainly linked to potential annoyance, privacy, or safety concerns. **Positive perceptions** were related to adjectives like “interested," “curious," or “fascinated." Some participants expressed that their feeling would **depend** on how competent they think the drone is, how socially acceptable it becomes, and the purpose of the drone.

Preference for a Machine vs a Living Being We inquired from the participants whether they would prefer a drone that displays social cues and emotions, making it more like a living being, or one that is purely machine-like. Surprisingly, responses were fairly evenly split. Participants who preferred a more social drone believed that it would result in better communication, personalization, and a more comfortable social presence, while also being less creepy. For instance, (P31) indicated that it “would make it easier to communicate with and talk to her." Meanwhile, (P7) “preferred something personalized like a personal butler," and (P35) said that “if you are interacting with an object, but the object does not learn how to interact with you, and it doesn’t learn anything from you, it’s very impersonal." For (P18), “it makes you feel like there’s someone there, and that’s nice," and (P36) indicated that they would prefer something closer to a living being “because I would see it more like a pet I think rather than like a weird thing watching me. Would be less creepy."

On the other hand, participants who were against a more social drone believed that it would be frightening, morally wrong, and potentially unnecessary. For example, (P12) said, “if there’s a personality built into it would freak me out a little bit." According to (P21), “it would feel less morally wrong if it was more machine-like ’cause we do use them as slaves [...] We might as well not give ourselves the moral pain." (P30) mentioned that “it depends on what they want it to do. For example, I wouldn’t like my coffee maker to be more human." (P35) added that “If it’s for taking pictures, it’s just a machine. If that’s an object that I have to live with every day, so eventually I will develop some feelings towards the drone."

Public, Personal and Company Drones In our exploration of a future in which drones are ubiquitous, we posited that companies and public services such as firefighters, police, and postal workers would utilize drones. We then asked participants whether they believed there should be differences between these drones and personal drones. Their answers fell into three categories: **aesthetic**, **regulatory**, and **functional** differences.

Participants expressed the expectation that such drones should be **clearly marked** to indicate the service or company to which they belong. One participant, (P4), suggested that “drones should have markings like they have on police cars and firefighter trucks" or “like people wear uniforms at work" (P21). Knowing the company or public service associated with the drone helps to “assess immediately what is the purpose of it" (P35). Additionally, some participants noted that it is particularly relevant for emergencies and public services as they may operate in areas where personal drones are not permitted, linking this to the second category of regulation.

Several participants recognized that public drones may have **more privileges** related to their role or the degree of emergency, but also emphasized the need to regulate these privileges to protect privacy. Some participants advocated for extending existing regulations to drones. For example, (P20) argued that “we have laws and regulations and human rights. [...] It should not be any different from what is supposed to be the actual practice of the police or the government". To support this, (P10) pointed out that “the police, unless they have a warrant, can’t come into your house and things. You’d expect the same from the drone".

Finally, some participants expect public drones to have **specific design characteristics** that are tailored to their role and not available to personal drones. For instance, (P24) mentioned the speed limit of a police drone chasing someone, (P9) thought about their size “if it needs to take out the trash," and (P31) stated that “firefighting drones obviously have to have equipment and things that the personal drone doesn’t need."

3.2.6 Discussion

In the following discussion section, we will analyze the findings of our proxemic experiment, which examined the influence of a drone’s flying altitude and framing on participants’ proxemic preferences. Our analysis will take into account the three proxemic functions (protective, communication, and arousal regulation) identified by Aiello [11], to provide a comprehensive interpretation of the results. Additionally, we will discuss the insights gathered from the semi-directed interview to further explore and clarify the quantitative measures, as well as to outline the current perception people have of the future of social drones and the use of Virtual Reality (VR) as an innovative approach for HDI proxemic studies.

Drones Above Us

In contrast to the behavior observed during Human-Human [342] and Human-Robot interactions, our study found that participants walked closer to a drone as its height increased.

This result is important because it challenges our initial assumption that drones are perceived as social entities and that people's proxemic behaviors around them are socially driven. In a setting where participants displayed naturally occurring proxemic behaviors through interactional methods without awareness of what was being measured (a valid approach), the Communicative proxemic function and Hall's framework were unable to account for this outcome. This suggests that these theories may not be relevant for explaining human-drone proxemics and highlights the need to explore alternative mechanisms.

Additionally, this unexpected result might stem from a misinterpretation of the spatial dynamics of drones. The term "tall" drone used in previous studies [107] may not be appropriate, as drones do not physically occupy the space beneath them in the same way that ground robots and humans do.

We propose that this result could be attributed to the proxemic protective function, which considers the participant's available space and perception of the drone's behavior. Unlike grounded robots and humans, drones interact with both physical and potential space differently due to their ability to move vertically and cover various locations. Observers often see drones high above, leading them to expect a drone that starts below eye level (1 meter) or at eye level (1.5 meters) to ascend. Just as we don't expect a pedestrian to suddenly veer off course, we don't anticipate a drone to abruptly land while performing a task. Consequently, when a drone is positioned high (above eye level, 1.95 meters), the space beneath it becomes perceived as partially available rather than being considered the drone's occupied space, leading to a reduced maintained distance. Our findings suggest that stationary drones should ideally fly above people rather than navigating around or below them in populated areas.

However, it is essential to note that the experimental setting does not reflect the complexity of the real world, where people and drones may interact in various environments. Future research could investigate how environmental characteristics, such as space, bystanders, and obstacles, impact the transferability of our results to other settings. Additionally, while previous research has used the stop-distance procedure to examine the impact of drone height in front human-drone interactions, our study measured participants' paths when walking around a drone in a co-existing context. Therefore, our work provides a complementary contribution to the field by utilizing a different methodology and measuring proxemic preferences in a significantly different context. Measuring minimum distances best aligns with the core objectives of our study by providing a natural indicator of personal space boundaries. We nonetheless acknowledge that this metric does not capture all aspects of proxemic behavior comprehensively such as trajectory, speed dynamic, orientations. The exploration of novel proxemic measures that encompass a broader range of behaviors presents another intriguing avenue for future research.

Framing, a Double-Edge Sword

Despite providing participants with clear expectations and understanding about the drone prior to their first encounter, the social framing used in our study did not have the anticipated effect. Based on the assumption that drones are perceived as social entities and guided by Hall's framework, we anticipated that enhancing participants' perception of the drone would foster a more positive relationship and lead to reduced maintained distances.

We believe that the expectations induced by the social framing did not align with the reality of participants' experience with the specific drone used in the study. This potential mismatch may have resulted in the opposite effect of what we had predicted, and instead of promoting social comfort, the framing may have highlighted the lack of social features in the drone's design and interaction. This suggests that a mere description is insufficient to make a drone "social", but it can make this dimension more prominent. This result also underscores the incorrect assumption that drones are inherently perceived as social entities and further challenges the applicability of the communicative function in explaining people's proxemic behaviors around drones.

However, beyond the interaction, our results indicate that some participants were prepared to engage with a social drone. Although they struggled to articulate their expectations, they clearly anticipated something distinct from a conventional AR Drone 2.0, implying that classic drones are not intended for social interactions. Other participants expressed disagreement with framing robots as social agents, preferring to regard them as tools. This disparity between the produced and individual frame may have resulted in greater physical distance, as previously observed by Banks et al. [37]. In contrast, the technical presentation was consistent with the drone's design and the overall experiment. Furthermore, some participants regarded the technical presentation as evoking a sense of safety rather than social interaction. Given that our participants came from scientific backgrounds, we believe that their pre-existing knowledge may have come into play. Not only were they more familiar with the terms used in the technical description, such as "deep reinforcement learning" and "neural network", but these words are also positively associated with advanced technology. As a result, the perceived threat level may have decreased or the drone's appeal may have increased, leading to a decrease in maintained distance. More broadly, as suggested by Entman [117], higher-level pre-existing frames, such as technology versus drone, can override or modify the produced frame, significantly influencing the outcomes.

While a technical framing served as an ideal contrast to the social one to verify whether we could artificially induce an increased sense of social connection through social framing, we may wonder what impact would a more "neutral" approach have had? Determining what truly constitutes a "neutral" framing is already debatable. The technical presentation was consistent with the drone's design and the overall experiment; hence one might argue it is already neutral. Another might say that a completely neutral approach would have been no framing at all, but then participants would be using their pre-existing frames of reference which is challenging to measure and control. Exploring the implications of different framing approaches, including potential neutral framing, could be an interesting avenue for future research. Additionally, while the social framing generated specific social expectations, which may have negatively impacted the results when unmet, we are curious about the outcomes if social features had been incorporated into the drone alongside this social framing.

Other Potential Factors: *Sound, Attention, Space and Drone's State*

The interviews conducted during the study uncovered several additional factors that could influence participants' proxemic behaviors. First, the noise produced by the drone was a notable annoyance for participants, causing them to avoid it, which hints at the potential role of arousal regulation in human-drone proxemics. Second, the task participants were engaged in seemed to divert their attention from the drone, potentially leading to a decreased perception of threat and a smaller maintained distance (protective function). This suggests that the nature of the activity individuals are performing can impact proxemic behavior, indicating a role for goal-oriented proxemics. Third, some participants noted the drone's size relative to the room, implying that both the size of the drone and the context of the environment might affect proxemic behaviors (related to available space and protective function). Finally, participants reported increased trust over time as they became more confident that the drone would not approach them, suggesting that a moving drone could elicit different behaviors as participants continuously adjust their expectations about the drone's movements (protective function).

The Future of Personal Drones

According to participants, in the future, people will naturally communicate with their drones to carry out various tasks both at home and outside. Personalized drones with advanced social features will coexist with more mechanical-looking ones. Private drones will differ in appearance to reflect their affiliation and function, while legal restrictions and capabilities will correspond to their purpose and allow them to operate in emergency situations. This vision aligns with the results of a previous study that explored social drones for the home environment from a user-centric perspective [200]. The feedback collected from participants in both studies was very similar regarding interaction preferences, applications, and the level of anthropomorphism desired in personal drones, indicating that people's projections for personal drones remain relatively stable over time. Furthermore, Herdel et al. [174] recently found that people have a more positive attitude towards drones' capabilities in severe contexts, which is consistent with the participants' feedback regarding the differences between public and personal drones. However, this exploration also highlights some challenges associated with the integration of drones into society, including high performance expectations, safety and privacy concerns, and complex design requirements.

Virtual Reality for HDI

The study used VR to examine how people behave when moving around a hovering drone. If the same experiment was conducted in the real world, safety measures would be necessary, which would impact the participants' perception of danger and their proxemic behavior. Instead, in the VR study, participants moved around freely in a one-to-one scale replica of the room. Some participants displayed risky behavior due to their curiosity, such as challenging the drone or trying to touch it. They even reported that they would be even more inquisitive if it were a real drone. VR allowed us to observe these types of behaviors that would be too dangerous to study in real-world experiments, but there are still questions about the ecological validity of VR.

While we limited our data collection to tracking the participants' positions over time using the VR headset, the expanding capabilities of VR technology present numerous avenues for exploring additional metrics. For example, the integration of eye-tracking technology in certain VR headsets offers the potential to quantitatively assess participants' focal points of attention during interactions with virtual elements, thereby enhancing our understanding of their cognitive responses and behaviors. Furthermore, other metrics pertinent to proxemics, such as participants' body orientations, movement trajectories, and speed, could be integrated into future studies using VR technology. We look forward to seeing how future research harnesses these opportunities to delve deeper into the realm of VR-based proxemic studies.

It should be noted that the results of proxemic studies in VR cannot be solely relied upon as an indicator of ecological validity. Our study demonstrates that VR can be valid, but not that VR is always valid. Our validity is based on extensive research and reflections on how VR could specifically influence proxemic behaviors, coupled with the deployment of specific mitigation techniques to limit its impact.

Nonetheless, while participants in the study reported behaving naturally in the VR environment, the variability in their presence levels highlights the subjectivity of this parameter. Researchers can only strive to enhance immersion, but cannot guarantee high presence. To improve ecological validity, one approach could be to determine a threshold level of immersion and then select participants accordingly.

However, high immersion alone may not be enough if other variables impacting the investigated phenomenon are altered. For instance, in this study, some participants expressed that they would maintain a greater distance from the drone in the real world due to safety concerns, indicating that threat perception in VR can be distorted. Since the protective proxemic function appears to be important in HDI, further inquiry was required to assess the extent to which VR alters threat perception during human-drone interactions compared to a real-world experimental setting.

Therefore, we conducted a Real-world/VR comparison study, presented in chapter 4, focusing on the protective proxemic function in HDI and assessing the extent to which observations differed between the two environments. This comparative study provided substantial evidence supporting the validity of the findings presented in the current chapter when compared to a real-world experimental setting [59]. However, we also propose that threat perception could be equally biased in both environments [59]. Thus, we emphasize the importance of conducting additional research to explore how our findings might apply to real-world scenarios. Despite these limitations, VR remains a valuable tool for investigating the potential impact of proxemic factors and can be used to generate hypotheses for real-world experiments.

3.2.7 Conclusion

To verify whether drones are perceived as social entities and if people's proxemic behaviors around them are socially driven, we examined the influence of two known proxemic factors in human-human and human-robot interactions: height and framing. We set expectations using Hall's frameworks [163], aiming to determine whether new empirical findings confirm and integrate well with existing research or if they are surprising and require further replication and scrutiny [264].

Our observations, obtained through interactional methods with accurate measurements enabled by VR technology, contradicted our expectations. Participants tended to get closer to the drone as it flew higher, and although social framing improved people's social perception of the drone, it did not result in closer maintained distances.

Regarding the flying altitute impact, we propose that this result could be attributed to the proxemic protective function, which considers the participant's available space and perception of the drone's behavior. This unexpected result might stem from a misinterpretation of the spatial dynamics of drones. The term "tall" drone used in previous studies [107] may not be appropriate, as drones do not physically occupy the space beneath them in the same way that ground robots and humans do. Unlike grounded robots and humans, drones interact differently with physical and potential space due to their vertical mobility. Observers expect drones to ascend from lower positions. Consequently, when a drone is positioned high (above eye level, 1.95 meters), the space beneath it is perceived as partially available, leading to a reduced maintained distance. Our findings suggest that stationary drones should ideally fly above people rather than navigating around or below them in populated areas, and underline the role of the protective function in human–drone proxemics.

Regarding the second variable, results suggest that the positive social framing successfully improved participants initial perception of the drone but also made the social dimension more prominent and created expectations. In particular, the social group reported that the drone lacked social features, and their expectations did not align with a typical drone creating a dissonance upon interacting with it. It seems that the absence of human-like features can contribute to the categorization of drones as cold machines seemingly devoid of social nuance. This, in turn, creates a barrier to people establishing meaningful social connections with drones.

We recommend further research to investigate the effect of social framing in association with socially-oriented features. Furthermore, researchers working in HDI should be mindful of how they introduce the drone to participants, as this could potentially bias the results.

Participants' expectations of future social drones were revealed through semi-directed interviews. They anticipate the use of personalized drones with advanced social features for various tasks both at home and outside, with different types of drones serving different purposes and being subject to legal restrictions. This aligns with previous studies and indicates stable projections for personal drones over time. However, the integration of drones into society presents challenges such as high performance expectations, safety and privacy concerns, and complex design requirements.

Finally, our study provides proof of concept for using virtual reality in HDI research. The ability to manipulate the virtual environment allows researchers precise control over experimental variables, such as the drone's appearance and behavior, which can be challenging to manage in the real world. Additionally, VR offers a highly immersive experience that closely mimics real-world scenarios and can be adapted to fit various situations and populations. Following the guidelines from our literature review (see section 2.3), we developed a valid environment for observing natural proxemic behaviors around drones. However, virtual experience remains subjective, and some participants reported an alteration in their threat perception, which might have influenced their behavior. This concern is specifically addressed in a real-world/VR comparison study presented in chapter 4. Overall, our work provides valuable insights into user behavior around drones and demonstrates the potential of immersive VR in the HDI field.

Transition to Study #2

- While participants' behavior was not socially driven in our initial study, potential reasons emerged suggesting that this might not always be the case. Our results challenged the assumption that drones are perceived as social entities but also highlighted the possibility for drones to embody social agents. Participants had expectations that were different from typical mechanical drones available today, indicating an unexplored design space where drones could be seen as social entities.

- Our interpretation of the results is that the absence of human-like features likely contributes to categorizing drones as cold machines, devoid of social nuance, which creates a barrier to establishing meaningful social connections. The difficulty in implementing such features in real-world settings with existing drones may have hindered research on social drones. This spark of potential, along with the opportunity to demonstrate Virtual Reality's capacity to expand research possibilities beyond real-world limitations, motivated us to conduct a second user study focused on the communicative function.

- In our second study, we implemented a virtual drone with a digital face to assess how different digital facial expressions and gaze behaviors would influence participants' perceptions of the drone and their proxemic behavior. By introducing these human-like features, we aimed to determine if social mechanisms would come into play through the drone's design. If successful, this would empower designers to infuse autonomous drones with social elements, triggering social mechanisms that enhance user engagement, well-being, and interaction.

3.3 *Study #2* - **Does a Face Make It Social?** Exploring the Impact of a Drone's Digital Facial Expressions on People's Proxemic Behaviors

3.3.1 Motivation

A key reason making it challenging to seamlessly integrate drones into our daily lives and promote close interactions is their mechanical nature, resulting from their efficient task-oriented design. Their mechanical design, including aspects like sound, behavior, and appearance, is often negatively connoted and associated with potential threats [59]. Moreover, the absence of human-like features can contribute to the categorization of drones as cold machines seemingly devoid of social nuance. This, in turn, creates a barrier to people establishing meaningful social connections with drones [58]. While there are scenarios where drones excel as efficient, task-focused roles, adhering to a uniform design approach that limits all drones to a non-social embodiment stifles the full potential of this technology in engaging our social nature. Establishing meaningful social connections is important for various reasons: it enhances user experience, improves safety and acceptance, facilitates collaboration, and fosters emotional engagement [54]. For instance, drones designed for delivery services or search and rescue operations that can interact socially may create a more satisfying and reassuring experience for users. Human cognition allows us to attribute intentions, thoughts, and emotions not only to living entities but also to non-living ones, such as machines. This cognitive trait empowers designers to infuse technology with social elements, triggering social mechanisms that enhance user engagement, well-being, and interaction [90]. The field of Social Robotics has traditionally focused on ground-based robots, but the unique nature of flying robots introduces a novel interaction paradigm with distinct challenges and opportunities, demanding a fundamental shift in perspective if we are to understand what it means to develop flying *social* robots.

The exploration of emotional facial expressions for drones has recently gained attention, exemplified by the work of Herdel et al. [172], who designed recognizable emotional faces for drones. Despite this notable advance in the field, the impact of these cues on how humans engage and interact with drones has not been investigated. Our study addresses this gap and evaluates the impact of digital facial emotions displayed by drones in real interaction scenarios. In addition, gaze direction, a powerful cue conveying a wealth of social information, is well-established as playing a significant role on influencing proxemic behavior among humans (or how close people will stand to each other). In Human–Drone Interaction (HDI) research, participants have referred to the drone's camera as its "eyes" [59], suggesting that the direction these 'eyes' point has the potential to influence people's perception of the drone. This leads us to question whether different drone "gaze behaviors" might significantly shape individuals' interpretation of displayed emotions, potentially resulting in distinct proxemic responses. In the present study, we address the following research questions:

- **RQ1:** How do the digital facial emotions of a drone affect individuals' proxemic behaviors? We expect participants will maintain a greater distance from the drone when it displays negative emotions (e.g., Anger, Sadness) compared to when it displays positive emotions (e.g., Joy).

- **RQ2:** How does a drone's gaze behavior impact user proxemic behaviors and their interpretation of displayed emotions? We expect participants will engage in closer proximity to the drone when it displays a "Follow" gaze behavior compared to an "Avert" gaze behavior, as the "Follow" gaze is perceived as more socially engaging and inviting.

To address these questions in a controlled and adaptable environment, we leverage the design flexibility of Virtual Reality (VR). VR allows us to overcome key limitations of real-world HDI proxemic studies while drawing upon a wealth of prior research validating its use in studying human interactions (see section 3.3.3). These limitations include: 1) technological constraints and feasibility; creating the drone we employed in the real world would have been challenging, particularly in ensuring stable flight movements with the added digital face and accurate drone gaze behavior relative to the participants' positions. One study attempted to add a face to a drone but had to use cables for stabilization [389], illustrating the difficulties of maintaining flight accuracy in real-world conditions when adding external components; 2) VR provides controlled and replicable experimental settings, eliminating the variability and unpredictability common with real drones, which are often difficult to control; and 3) safety concerns, which pose significant challenges with real drones. Experimenters are often forced to implement safety measures, such as imposing a minimum distance [5, 107, 164], using transparent walls [164], fixing the drone's position [107, 389], or employing fake drones [82]. Some researchers [58, 107, 235] have criticized these methods, pointing out the potential impact safety measures may have on participants' reactions near drones, thereby questioning the ecological validity of such approaches. Moreover, VR enables us to accurately measure participants' movements while providing them total freedom to navigate, better aligning with methodological requirements to observe natural proxemic behaviors as opposed to the typical stop-approach procedures used in real-world studies.

Study Design & Methodology In our study, 25 participants are immersed in a virtual environment, where they interact with and navigate around a drone displaying various digital facial emotions (Joy, Sadness, Anger, Surprise, Fear) and gaze behaviors (Follow and Avert). However, due to their low recognition accuracy (76% for Surprise and 54% for Fear), we have chosen to exclude these expressions—Surprise and Fear— from the main analysis. This decision ensures a more focused examination of the reliable and accurately recognized emotional cues.

Results Our results reveal that the drone's gaze significantly influences participants' proxemic behaviors, with their responses mirroring those observed in human interactions. In addition, we found that participants who lacked prior familiarity with drones or held neutral to positive attitudes toward these aerial machines were also significantly influenced by the drone's digital facial emotions. Their favorable disposition toward robot interactions appears to heighten their receptiveness to the emotional signals conveyed by the drone. Once more, participants' spatial dynamics when confronted with varied emotional expressions on the drone coincide with patterns observed in human–human interactions [298, 319] and human–robot interactions [43]. This discovery suggests that the utilization of social cues bears potential for facilitating the integration of drones into diverse environments and tailor their design and behavior to suit specific individuals and situations. We shed light on how the social proxemic function [163] influences individuals' personal space boundaries in human–drone interactions. Importantly, our work is the first to show that people respond to drone social cues similarly to how they react in human–human interactions in terms of proxemics, or where they positions their bodies in relation to the drone [298, 319] and human–robot interactions [43].

The drone's 3D model, audio files and images, virtual environment, and datasets utilized or produced in this study are accessible to the public through a dedicated GitHub repository (see [55]).

3.3.2 Related Work

This section offers an overview of the research landscape on the specific topics addressed in this study, including social drones, the communicative proxemic function, and digital facial expressions and gaze. It sets the stage for our study by summarizing key findings and identifying gaps in these areas. A detailed literature review of proxemics and virtual reality is provided in chapter 2.

Social Drones

Definition Baytas et al. [38] offered a broad definition of social drones, characterizing them as autonomous entities that operate within inhabited environments, highlighting the inevitability of social interactions between these autonomous drones and humans. This perspective extends the notion of the social dimension to encompass various autonomous machines, irrespective of whether their primary function is predominantly social. However, this definition can be misleading, as it may lead researchers to assume that the social dimension is prominent in interactions with any drone, even those that appear purely mechanical. Our previous research suggests this is not the case.

Alternatively, drawing inspiration from the field of Social Robotics [54], another approach envisions Social Drones as entities designed to engage users on a deeper level, promoting well-being and facilitating interactions. These drones are equipped to communicate naturally through verbal and non-verbal cues, comprehend human behaviors to respond appropriately, and effectively interact with individuals to achieve their objectives. In summary, the former perspective delineates when the social dimension becomes relevant, while the latter furnishes an aspirational description of the attributes social drones should aspire to embody. By integrating social cues into existing drones, our work represents a progression from the first definition toward the second, aiming to enhance drones with the capabilities outlined in the latter description.

Current Research on Social Drones Social drones can be categorized as a distinct subgroup within the broader field of Social Robotics. However, whereas the focus of social robotics has traditionally been on the development of ground-based robots, flying robots offer a novel interaction paradigm full of new potential for social engagement. Drones possess distinctive attributes, notably their capacity to fly, their striking appearance, and the sounds they emit. Furthermore, they may not evoke the same associations in the popular imagination as traditional ground-based robots do. Early research indicates that insights derived from Human–Robot Interaction (HRI) studies with ground-based robots do not seamlessly apply to Human–Drone Interaction (HDI) [5, 107]. This substantial shift in the design space of Social Robotics underscores the necessity of treating drones as an entirely new and distinct entity, requiring fresh perspectives and approaches.

In this context, a growing number of researchers have explored drones as potential agents in social contexts, including domestic drones designed for home environments [140, 200, 270], flying companions [141, 208, 237], and even emotional support drones [124]. Researchers have rapidly investigated ways for drones to naturally communicate with others through various means, such as lights to indicate communication intentions [149] or direction [345] and flying movements to convey emotions [79, 322], intent [344] and the drone's state [106].

Drone's Emotional Face Within this communication perspective, Herdel et al. [172] departed from the traditional drone design and introduced specifically designed digital displays for drones to convey facial emotional states. Their study efficiently demonstrated that people could recognize a drone's emotions and attribute narratives and social meaning to them. However, it is important to acknowledge that recognizing facial emotions on a screen and deducing their origin is a somewhat distant experience from a real-life emotional interaction.

While Herdel's work demonstrates the potential for using social mechanisms to influence human–drone interaction, it remains unclear how these findings would translate into real-world scenarios. For example, another study that portrayed the drone as a positive social entity significantly improved participants' perceptions of the drone before interaction [58], but this positive perception did not lead to actual behavioral changes during interaction. This highlights the importance of assessing the impact of social cues beyond mere surveys and observing participants' natural behaviors in interaction scenarios. Our work aims to address this gap and takes a step forward by empirically testing how people's behavior and perceptions of the drone change based on the displayed facial emotions during interaction and navigation around it.

Drone's Eyes Furthermore, in Herdel's work, the drone's eyes were integrated with the overall expression rather than considered as separate conveyors of meaning. Yet eye gaze plays a vital role in human–human interaction, conveying information, regulating social intimacy, managing turn-taking, and expressing social or emotional states [8, 24, 210]. Notably, the fact that people often perceive the drone's camera as its eyes suggests that it may already play a role, even though it has not been formally investigated in Human–Drone Interaction [59]. While the effects of eye gaze have been demonstrated in Human–Robot Interaction (HRI) [8, 263], it remains unclear how these findings translate to Human–Drone Interaction. Our work aims to address this gap by considering the drone's gaze as a separate variable. We present two opposing gaze behaviors: following and averting gaze, allowing for a direct comparison with similar studies in human–human [31] and human–robot interactions [263]. Moreover, the subtlety of the message conveyed by emotional facial expressions can significantly change with different gaze behaviors. Admoni and Scassellati's review on Social Eye Gaze in Human–Robot Interaction [8] underscores the complementary relationship between gaze and facial expressions. While previous studies have explored the effects of robot gaze behaviors, Admoni and Scassellati suggest that further research into their interactions with other gestures could enhance our understanding of nonverbal communication in robotics. Our work also addresses this gap by examining the relationship between the displayed gaze and digital facial emotions and how it may impact the interpretation of the drone's emotional state in the context of Human–Drone Interaction.

The transition from conceptual or hypothetical drone designs to observing real user behavior during interactions is facilitated by the design flexibility provided by Virtual Reality (VR). VR uniquely allows for testing and observing innovative drone designs in interactive scenarios, overcoming challenges such as logistical constraints, safety concerns, and technological limitations associated with real-world implementations. Moreover, VR offers researchers the advantage of controlling confounding variables, reducing development time, and providing a controlled environment for detailed analysis, making it a valuable tool for exploring user behavior in HDI. VR has been effectively employed to assess the appearance of innovative drones [77, 200]. In fact, it has been classified as the second-best method in terms of realism, just behind collocated flight, according to Wojciechowska et al. [382]. Moreover, VR is considered a safe and reproducible environment for testing. A recent comparative study indicates that when controlling for potential influences of VR on the phenomena of interest, as discussed in section 3.3.3, the outcomes in VR closely align with those observed in real-world experimental settings [59].

Human–Drone Proxemics

Following Leitchmann et al.'s [227] recommendation to take an objective standpoint on proxemic functions in HDI, it becomes evident that the defensive function significantly shapes individuals' proxemic behaviors around drones. Several studies have highlighted the protective proxemic function in HDI [4, 58, 362, 391]. Our own dedicated study, detailed in chapter 4, confirmed and further theorized this function [59]. We found that individuals' personal space boundaries around drones are closely linked to their perception of the threat posed by the drone. This perception is inherently connected to the drone's design, underscoring the importance of exploring design modifications, such as incorporating social cues, to address this issue.

Additionally, the sound emitted by drones has been identified as a significant factor prompting individuals to increase their distance [76, 370, 391], suggesting the relevance of the arousal regulation function in this context.

However, the role of the social proxemic function described by Hall remains contentious. Early observations indicate that this function may not be as prominent, as noted in our first study (see previous section) [58]. In our earlier study, portraying the drone as a positive social entity significantly improved participants' initial perceptions of the drone . However, this perception did not persist during interaction, and no significant proxemic differences were observed. Participants primarily viewed the drone as an obstacle, a failure we attributed to the drone's highly mechanical and non-social nature, as supported by participant feedback. Interestingly, Yeh et al. [389] found that adding a face to a drone resulted in decreased maintained distances. Yet, such result could be explained by the decreased saliency of the threatening components of the drone [59], which is supported by the feedback "I concentrated more on the face of the drone and therefore did not think so much about the propellers". Their study alone does not provide conclusive evidence about drones' potential to exert substantial social influence that would lead to actual behavioral changes.

In contrast, the field of Human–Robot Interaction (HRI) boasts a wealth of studies indicating that humanoid ground robots can indeed be perceived as social agents and wield significant social influence. Of particular interest to this study, Bhagya et al. [43] found a significant effect or robots' facial emotions, presented in the form of emojis, on individuals proxemic behavior when initiating conversation. In particular, Anger led to individuals maintaining the greatest distance, while expressions of Sadness resulted in the closest proximity. Furthermore, an influential study by Mumm and Mutlu [263] examined the role of robots' gaze in influencing proxemics. Their research revealed that people consistently maintained a greater distance from the robot when it maintained eye contact compared to when it averted its gaze, similar to behavior observed in human social interactions.

In light of these contrasting observations, our study seeks to unravel the role of the social proxemic function in HDI. While the absence of social features in drones has previously been linked to the failure to establish a social connection, we anticipate that the digital facial emotions designed by Herdel will enable the social proxemic function to play a substantial role in shaping individuals' proxemic behaviors in the context of Human–Drone Interaction.

3.3.3 Methodology

This study explores the impact of the drone's digital facial emotions and gaze behavior on human participants' proxemics (how close they are willing to get to the drone) during two distinct tasks: 1) engaging in a conversation with the drone, and 2) walking around the drone to retrieve information displayed on its back. To address the complexities of human–drone proxemics, we have designed a methodology that prioritizes ecological validity and aligns with the latest findings in the field. All manipulations, measures, sample size justification, and main hypotheses were preregistered on the Open Science Framework (OSF) before data collection: https://osf.io/49b2t. We report all manipulations and measures in the study, in line with recent proposals [138].

As noted in Hall's early work on social proxemics, distancing from others is not a conscious, rational decision but an instinctive response to various sensory inputs [163]. Some researchers argue that using the stop-distance procedure may compromise ecological validity, as it forces participants to consciously think about distancing [58]. Instead of this common method used in Human-Drone Proxemics studies (e.g., [164, 235, 389]), we chose a more natural approach to observe participants' proxemic behaviors, similar to the methods used in previous works (e.g., [31, 43, 58, 263].

Approach and initiate dialog In the first phase of our methodology, participants were instructed to approach and initiate a conversation with the drone. This approach serves multiple purposes. First, it temporarily directs participants' attention to the drone, allowing for a more focused perception of the drone's face, which contains the stimuli of interest. Additionally, this conversation task may prime participants to perceive the drone as a social agent rather than as a mere obstacle in their path. This methodological choice draws inspiration from Bhagya et al. [43], who examined the influence of emojis in conveying a robot's emotional state on proxemic preferences. By adopting a similar task, we facilitate a meaningful comparison of proxemic preferences between ground-based and flying robots, offering valuable insights into the role of drones in social interaction.

Retrieve information on its back Following the conversation, participants are required to navigate around the drone to access visual information (i.e., identify basic 2D shapes) located behind it. This navigation task, inspired by the work of Bailenson et al. [31] and Mumm and Mutlu [263], allows us to observe participants' paths and the distance they maintain while circumnavigating the drone (see Figure 3.9). Unlike previous studies, we employ shapes such as squares, circles and triangles (see Figure 3.13), rather than words, to prevent word readability from influencing participants' approach behaviors.

Our research also delves into the interplay between gaze and digital facial emotions. Alongside manipulation checks, participants provide responses to questions akin to those used in Herdel et al. [172] to evaluate the interpretation of digital facial emotions, their emotional im-

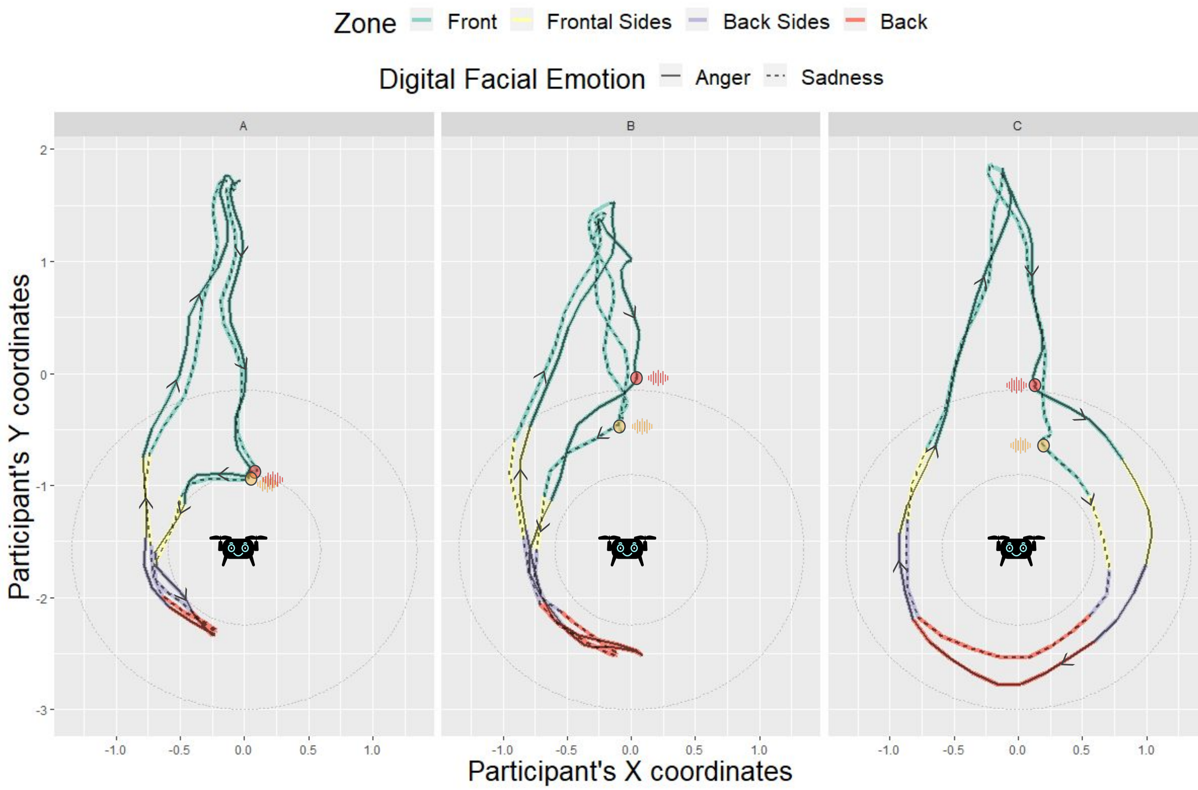


Figure 3.9: Visualization of participants' trajectories tracked through the VR headset during the task. We've chosen three distinct profiles to emphasize the variability in proxemic sensitivity to the drone's expressions. For clarity, we present paths only for the Follow gaze behaviors, comparing Anger and Sadness expressions. The points where participants paused to initiate conversation are marked by speech logos and circles (red for Anger, orange for Sadness). We can observe that participant A exhibits highly consistent proxemic behavior unaffected by the drone's expressions. In contrast, Participant B exhibits variability primarily within the front zone, maintaining a greater distance when initiating conversation with Anger compared to Sadness. Notably, this difference tends to diminish afterward, possibly illustrating a phenomenon elaborated in section 3.3.5 of the discussion. This phenomenon suggests that participants may shift their perception of the drone from a social entity to a mere obstacle due to the nature of the assigned task (from engaging in conversation to reaching a point behind it). Lastly, Participant C exhibits a pronounced influence of the digital facial emotions, remaining visibly important in the front (blue path) and frontal side (yellow path) zones, and diminishing upon return to the starting point. This participant also follows a distinct path to accomplish the task.

pact, and the extent to which participants perceive them as relevant to themselves. Detailed information about the use of Virtual Reality (VR) in this study and the design of the stimuli of interests is provided in the next section.

Setup and Apparatus

Design of Virtual Environment This study employs the experimental setup described in section 2.3.2. Participants wore a Pico Neo 3 Pro Eye and they engaged in conversations with a drone and navigated around it to access visual information within the virtual space (see Figure 3.10 and Figure 3.9). Additionally, participants employed the handheld controller to interact with 2D virtual screens projected onto virtual models of computer screens within the virtual environment. This allowed them to complete the task and respond to questions. Similar to the actions of pointing and clicking with a mouse on a computer, participants utilized the ray casted by the controller for pointing and the trigger button to initiate the click action. The Unity project is available on the Thesis GitHub repository [56].

Figure 3.10: The experimental room (right) next to their virtual replica (left) in Unity 3D. Participants' paths were recorded in the simulation allowing the accurate assessment of proxemic preferences around the drone, in a safe and realistic environment.

Ecological Validity in Virtual HDI Studies While the ecological validity of virtual Human–Drone proxemics studies has not yet been formally demonstrated, prior research suggests its potential as a valid methodology. To align with best practices, we followed a protocol derived from an extensive literature review on VR concepts and a real-world/VR human-drone proxemic study (presented in chapter 4). This approach aimed to optimize ecological validity and facilitate the external evaluation of virtual HDI experiments [59]. This multi-step approach comprises:

1. Identifying the relevant underlying mechanisms associated with the variables under study.
2. Recognizing how VR technology may influence these factors.
3. Outlining strategies to minimize VR's influence on the observed outcomes.

The general challenges associated with using VR for proxemic studies (i.e. motor abilities, distance compression), along with the solutions implemented in our experimental setup, are discussed in section 2.3.2.

In our study, we specifically explored social proxemics by investigating how social cues displayed by a drone influence individuals' proxemic behaviors. Importantly, there is, to our

Figure 3.11: Illustration of the alignment between the Real and Virtual Environments. As the VR safety boundaries (blue grid) are approached in VR (left image), the real-world environment seamlessly blends with and ultimately supersedes the virtual environment (middle and right image). While the safety boundaries were originally aligned with the room dimensions during the study, for this demonstration, the boundaries have been modified. This adjustment allows us to showcase the spatial alignment between the two environments.

knowledge, no existing evidence to suggest that virtual reality affects the perception or interpretation of social stimuli, such as the drone's digital facial emotions and gaze behavior. Indeed, researchers have extensively used VR in the field of social psychology to investigate the impact of factors like facial emotions [298] and various gaze behaviors [31] on interpersonal space.

Design of Drone and Stimuli

Drone's characteristics To enhance ecological validity and ensure participants responded to the social drone as if it were real, we used a 3D model of an actual DJI Tello drone (98 x 92.5 x 41 mm) paired with spatial audio based on a recorded sample of the drone's sound. The sound was sourced from a drone sound test video [375] and adjusted in pitch to closely match the real DJI Tello drone owned by the experimenter. This audio was spatialized using Unity's 3D sound engine, with the drone object as the sound source and the participants' VR headsets as the receivers. The sound intensity dynamically adjusted with the distance between the drone and participants, and the audio balance shifted between the left and right channels based on participants' orientation relative to the drone. This setup aimed to create a more immersive and realistic auditory experience, closely mimicking the presence of a real drone. We have also replicated its size and animated the virtual drone to include rotating propellers and simulated hovering imperfections, such as shakes. Similar techniques have successfully induced a sense of threat from the drone and received feedback describing the virtual drone as real [59]. The primary missing component is the airflow produced by the rotating propellers, which we acknowledge as a limitation and discuss further in section 3.3.5.

The drone hovered in a stationary position at eye level with the participants. This positioning aimed to maximize the visibility of the stimuli (i.e., the drone's face) and prevent potential height differences from affecting proxemic preferences. Previous research indicates that engaging with the drone at eye level feels more natural for participants, regardless of their cultural background, when concerns about physical harm are absent [76, 109].

To minimize the influence of non-social factors, such as perceived threat and noise annoyance, the virtual drone was equipped with protective propeller guards, and its flying noise was reduced to a subjectively low annoyance level. While this may seem like a limitation in terms of the transferability of results to real-world drones, it also serves an important purpose by helping isolate the specific social phenomenon under study. This trade-off is further discussed in section 3.3.5.

Digital Facial Emotions The digital facial emotions displayed on the drone's screen in this study were designed by Herdel et. al [172]. They developed cartoon-like facial emotions for drones that rely on Action Units to convey specific emotions that are highly recognizable to human interactants. Their work centered on the six basic emotions: Joy, Sadness, Fear, Anger, Surprise, and Disgust, with three varying levels of intensity: low, medium, and high. This emotional framework has been selected due to evidence demonstrating the universality of basic emotions across diverse cultures [111], and its wide use across studies exploring the perception of emotion displayed by robots [53, 71]. These motivations remain valid for our work and are strengthened by Bhagya et al. [43] who used the same model to investigate the impact of ground robots' emotional emojis on proxemic preferences. In Herdel's study [172], each categorical emotion has been successfully conveyed with high recognition rates, except for Disgust, which was often confused with Sadness and reached 29% recognition. Therefore, Disgust has been removed from our study. Within each emotion category, medium-intensity facial expressions have reached the highest recognition scores, motivating their use in our study.

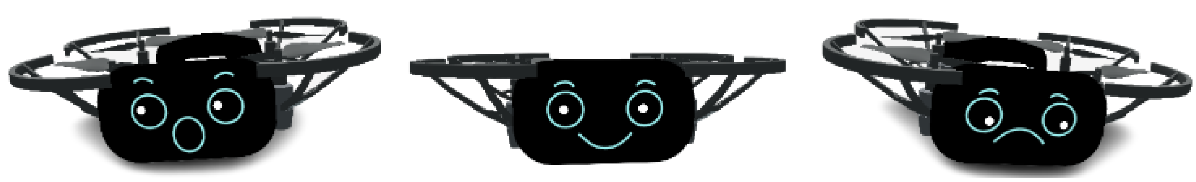


Figure 3.12: Some drone designs inspired by Herdel et al. [172] used in the study: from left to right, representing Surprise, Joy, and Sadness, with diverse gaze behaviors illustrating potential interactions with the drone's digital facial emotions.

Gaze behaviors Another critical aspect of our study is the design of the drone's gaze and behavioral characteristics. It is imperative that participants can readily identify where the drone is directing its gaze (and thus attention), and interpret this as a social cue, rather than an uninformative visual display. Extensive prior research has indicated that perceived accuracy in gaze direction diminishes when the gaze is presented from the side [14], restricted to head movements, or projected onto a 3D sphere instead of a 2D screen or 3D face-like mask [98]. In this study, we use the white pupils of the simplified eyes to indicate the drone's gaze direction (see Figure 3.12). The drone has a limited field of view which may require "head movements" corresponding to drone rotation. As in Baileson et al. [31], the drone's rotation is limited to 85 degrees in either direction, imitating a standing person who can only move their head. One potential challenge associated with employing flat screens to depict gaze is the "Mona Lisa effect," a phenomenon where observers perceive that the gaze follows them from any angle [261]. We ask specific questions (see section 3.3.3) to assess the extent to which this phenomenon occurred during the experiment, using manipulation checks for the gaze conditions (Follow/Avert). To enhance the human-likeness of the drone's gaze, we have introduced organic features such as blinks, smooth pursuits when the drone's gaze follow participants, limited focused time and saccades when it fixes random points to avoid eye contact. These nuanced behaviors contribute to a more lifelike representation of how a human might gaze and interact socially. In the Follow condition, the drone maintains sustained eye contact with the participant and smoothly rotates when they move beyond the limits of its field of view, with the rotation constrained to a maximum of 80 degrees. If participants venture beyond this "watching zone," the drone gradually returns to its default orientation. Conversely, in the Avert condition, the drone's gaze is directed at random points within its field of view and occasionally incorporates subtle rotations, simulating the behavior of someone glancing at objects in front of them. Importantly, the Avert condition deliberately avoids eye contact with the participants, focusing instead on points distant from their position.

Task-Related Stimuli Participants perform two tasks in this study. First, they interact with the drone by asking it for a specific letter, which the drone communicates vocally. The audio stimulus originates from a male English speaker, whose recording of the alphabet was sampled to extract the relevant letters for the study. The drone serves as the audio source, delivering the letter vocally to participants through their headsets. For replication purposes, the audio files have been uploaded to the study's GitHub repository [56].

After receiving the letter from the drone, participants must identify the corresponding shape displayed on the back of the drone (see Figure 3.13). These shapes were custom-designed by the experimenters and integrated as sprites on the drone's back display. The shapes have been made available on the experiment's GitHub for reproducibility. The visual letters, however, were generated internally using Unity's built-in TextMeshPro component and can be easily recreated within any Unity based environment [56].

Study Design

The study employs a 5x2 within-subject design with two independent variables: "Facial Emotion" (5 levels: Anger, Fear, Sadness, Surprise, Joy) and "Gaze Behavior" (2 levels: Follow, Avert). Additionally, we explored whether the gaze behavior influences the interpretation of perceived facial cues. The order of experimental conditions is randomized using a Latin square design. Detailed information on the design of the independent variables for the digital facial emotions and gaze behaviors is provided in section 3.3.3.

The primary dependent variable is the measured physical distance from the drone maintained by participants while performing tasks, which is calculated using tracking data from the headset within the virtual environment (see Figure 3.9). All the collected data are as follow:

Proxemic measure In both tasks, we utilized the minimum distance from the drone (in meters) maintained by participants as the primary proxemic index. This approach aligns with established methodology in prior research [31, 58]. Calculating the average distance participants maintained is often unsuitable due to the varying time spent at different distances in the dynamic tasks, which can lead to inconsistent outcomes. Additionally, we considered the impact of participants' relative orientation to the drone on their proxemic behavior, as observed in a previous HDI study [382]. Instead of prescribing specific walking angles for participants, we opted to maintain a natural task environment. To achieve this, we collected data on participants' and the drone's relative orientations as participants moved naturally around the drone. We subsequently calculated the proxemic index for different angles. This allowed us to define four distinct zones corresponding to the *Front* of the drone (-45 to 45 degrees), *Side Front* (45 to 90 and -45 to -90 degrees), *Side Back* (90 to 135 and -90 to -135 degrees), and the *Back* of the drone (from -135 or 135 to 180 degrees), as illustrated in Figure 3.9. This approach enhances the granularity of our proxemic analysis.

Self-Assessment Manikin (SAM) + Likert Scale ratings We used the Self-Assessment Manikin (SAM) to assess the impact of the drone's displayed emotions on participants [52]. SAM evaluates affective dimensions including valence, arousal, and dominance. To complement these measurements and enhance insights into participants' emotional responses, we incorporated Likert scale questions inspired by Herdel et al.'s coding schemes [172]. These Likert scale questions assessed various aspects, including:

- **Affect:** How much participants believe the drone's emotional state impacts their own emotional state.
- **Empathy:** The degree to which participants feel that they share the drone's emotional state or have empathy towards the drone.
- **Self-Relevance:** The degree to which participants perceive that the drone's emotional state reflects how it feels about them.
- **Direction of the drone's state:** Whether the drone's expression seem to precede a future action.

The specific Likert scale questions can be found in the Appendix for reference.

Manipulation Checks To ensure the effectiveness and reliability of the experimental manipulation of independent variables, we employed manipulation checks. After each condition, participants answered questions designed to confirm that the intended emotions have been successfully conveyed and that the two gaze behaviors (Follow/Avert) have been distinctly perceived. The questions included: **1)** Rate the extent to which you felt the drone was looking at you (Answers: Not at all, Slightly, Moderately, A lot, All the time). **2)** What emotion would you associate with the drone's facial expression? (Answers: Joy, Sadness, Anger, Surprise, Fear).

Pre-experiment Questionnaires Before the experiment commenced, participants completed questionnaires aimed at evaluating potential confounding variables related to individual traits. We administer the Negative Attitudes towards Robots Scale (NARS) and Robot Anxiety Scale (RAS) questionnaires, originally developed to assess communication avoidance behaviors during human–robot interactions [267, 268]. We adapted these questionnaires to our research context by replacing "Robot" with "Drone." We also gathered information on various demographic variables, including gender, age, previous drone experience, pet ownership, and cultural background [109], which may act as potential confounding factors in the context of Human–Drone Proxemics. Participants were required to complete the demographic questionnaire before the experiment.

Post-experiment Questionnaires After completing the experiment, participants responded to the Igroup Presence Questionnaire (IPQ) [315] and the Fast Motion Sickness Scale (FMS) [204]. These questionnaires assessed the level of immersion experienced within the virtual environment and any symptoms of motion sickness, helping us judge the quality of the immersive virtual environment.

Protocol

Participants received an invitation that outlined an experiment designed to explore people's perceptions of social drones in a virtual environment. This invitation included links to essential documents, such as the Participant Information Sheet, Informed Consent Form, a Demographic Questionnaire, the Negative Attitudes Towards Robots Scale (NARS), the Robot Anxiety Scale (RAS), and a scheduling link via Calendly to book their participation slot. On the designated date and time, participants were welcomed at the laboratory and guided to the experimental room. During this session, the experimenter reviewed the study's purpose and procedures, and participants could ask questions and were asked to provide written informed consent. Simultaneously, the experimenter ensured that the real and virtual positions of the headset match (see Figure 3.11). Participants then equipped the VR headset, immersing themselves in the replica of the experimental room.

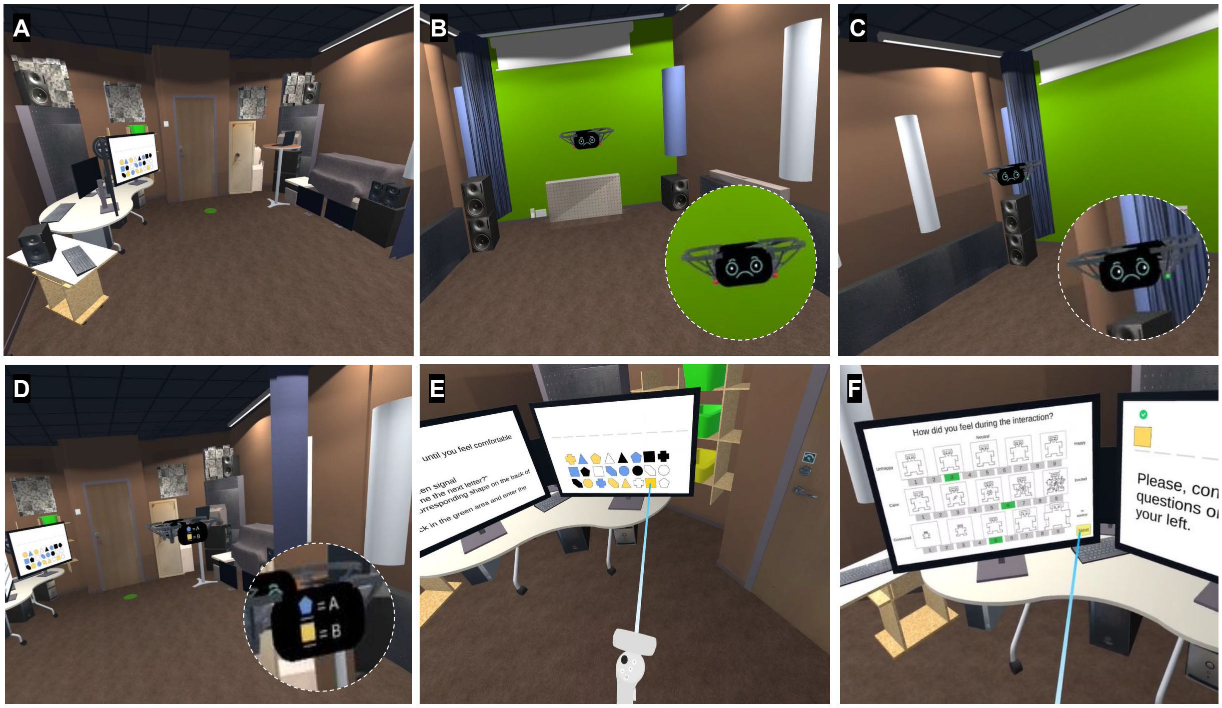


Figure 3.13: **A–** After taking a moment to familiarize themselves with the virtual environment, participants stand on the green spot—both the starting point and the interaction zone with virtual screens in the study. **B–** From this starting position, participants approach the drone, featuring a combination of Face and Gaze conditions (illustrated here as Sadness and Follow). They initiate communication with a "Hey," signaling their intent. The drone's light turns green, prompting participants to ask for the next letter with "Can you tell me the next letter?" The drone verbally communicates the letter "B," which participants use in the subsequent steps. **C–** Participants navigate around the drone to access the screen on its back. **D–** On the screen, participants identify the shape corresponding to the letter provided by the drone. In this specific example, the letter "B" corresponds to the correct shape, which is represented by the yellow square as the next element in the shape sequence. **E–** Returning to their initial position, participants input the correct shape in the shape sequence. Incorrect inputs can be removed by clicking on them, while correct inputs prompt questions on the left screen. **F–**Participants, using the controllers (see section 3.3.3), then answer questions, including a Self-Assessment Questionnaire and Likert scales, as detailed in section 3.3.3. The study cycle, starting from step A, continues until participants successfully complete the shape sequence, with the sequence's length aligned with the number of distinct sets of conditions.

The content displayed in the virtual environment and the steps participants undergo are depicted in Figure 3.13. After a brief familiarization session in VR, during which participants had the opportunity to walk in the room and observe the environment, they were instructed to stand at the indicated spot in the virtual environment. We reminded them of their task and encouraged them to take their time. The task required participants to enter a code composed of shapes in a specific order, unknown to them.

1. **Approach and initiate dialog:** To reveal the next element of the sequence, they needed to approach the drone and vocally request a letter. The corresponding shape on the screen,

located on the back of the drone, indicated which shape must be placed next.

2. **Retrieve information on its back:** Participants had to move around the drone to view it, and then return to the virtual screen to provide the shape entry.

Whenever a new element was added to the sequence, participants had to answer a series of questions, using the handheld controller (see section 3.3.3), that appeared on the computer screen placed on the table. They clicked the 'Next' button to proceed to the next questions, until they were instructed to repeat the procedure from the beginning. Once the sequence was completed, and the final questions were answered, participants could remove the headset. They were then invited to complete the IPQ and FMS questionnaires on the experimenter's computer.

The whole experiment took approximately 30 minutes. Participants were debriefed and thanked in the end.

Participants

For this study, we recruited a total of 26 participants. However, 25 were retained for analysis, as one participant, who openly identified as neurodivergent, faced challenges in completing the tasks and was consequently excluded. The final sample consisted of 11 males, 12 females, 1 non-binary individual, and 1 who preferred not to disclose their gender. The chosen sample size adheres to the standards set by the HCI field for within-subject designs [70] and is comparable to or larger than the sample sizes used in previous studies related to human-drone proxemics, some of which employed similar or smaller sample sizes [107, 389]. The participants' ages ranged from 23 to 53, with a mean age of 31.58. The participants were from various regions: Europe (21), Asia Pacific (3), and the Middle East (2). Regarding their prior experience with drones, 2 participants had never seen a drone, 17 had seen a drone, and 9 had used them. Recruitment was conducted through online advertisements and word of mouth within the institute. All participants provided informed consent before participating in the study. The participants received a bottle of flavored water and a cereal bar as compensation. The research received ethical approval from the University of Glasgow Ethics Committee (reference number: 300220159). Prior to the experiment, participants completed a demographic questionnaire, the Negative Attitudes Toward Robots Scale (NARS), and the Robot Anxiety Scale (RAS).

3.3.4 Results

In the following section, we present the outcomes of our statistical analysis. As mentioned earlier, the proxemic index employed in this study refers to the minimum distance observed during interactions with the drone, assessed across four distinct zones: the front, front sides, back sides, and back of the drone. To assist readers in navigating through the results, we incorporated summary boxes and a color-coded system. Moreover, Figure 3.14 provides a visual overview

Table 3.2: Demographics Summary

Number of Participants		25
Gender	Male	11
	Female	12
	Non-binary	1
	Prefer not to say	1
Age	M	31.58
	SD	8
	Range	23-53
Origin Region	Europe	20
	Asia Pacific	3
	Middle East	2
Drones' Experience	Not at All	2
	A Little	14
	Quite a Bit	9
	A Lot	0
VR Experience	Not at All	2
	A Little	16
	Quite a Bit	7
	A Lot	0
Pet Owner	Yes	16
	No	9

of the primary measures and examinations conducted in this study. (Note that the colors in the figure are unrelated to the following color code.)

Blue boxes summarize the verified impact of potential confounding variables measured prior to the study via questionnaires, on participants proxemic behaviors.

The green box outlines the results of validating the independent variables in the study.

Yellow boxes emphasize the findings of the main proxemic analysis, which involves examining the influence of the drone's digital facial emotions and distinct gaze behaviors on individuals' proxemic behavior. A more detailed analysis explored significant impacts observed within subgroups of participants.

Red boxes spotlight the results of the emotion interpretation analysis, delving into participants' perception and interpretation of the displayed social cues during interaction with the drone.

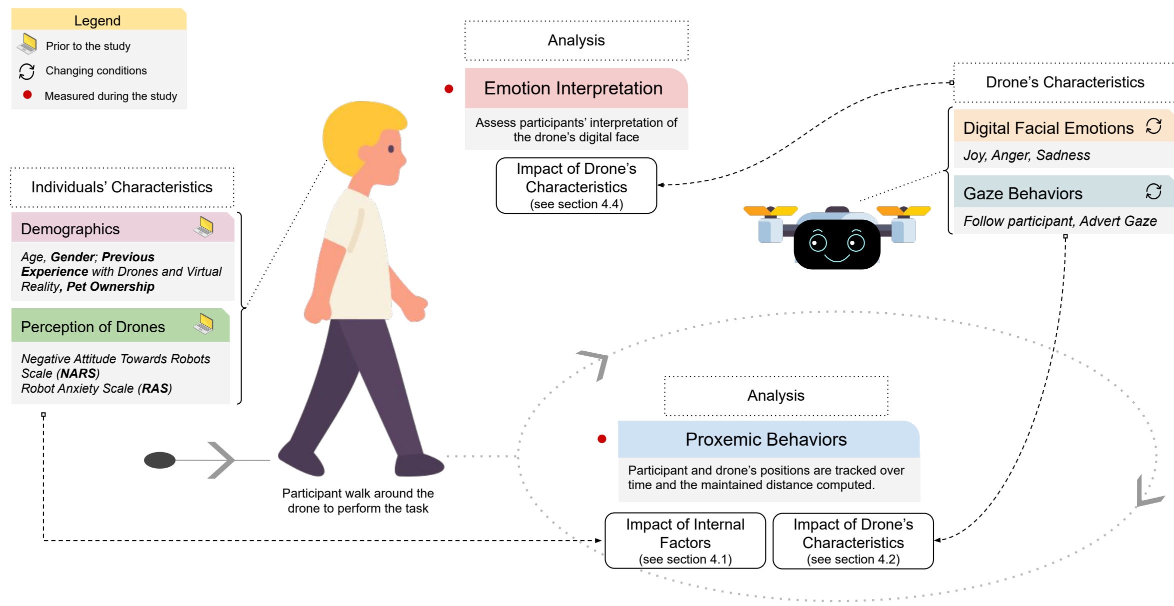


Figure 3.14: A schematic summary of the primary measures and examinations conducted in this study is provided. The investigation included assessing the potential impact of confounding factors related to individuals' characteristics on proxemic behaviors while navigating around the drone, as reported in section 3.3.4. Furthermore, the study examined the influence of the drone's digital face, encompassing various digital facial emotions (*Joy, Anger, Sadness*) and gaze behaviors (*Following participants, Adverting gaze*), on proxemics behaviors, detailed in section 3.3.4. Additionally, the interpretation of these cues was investigated, with results presented in section 3.3.4.

Confounding Variables

Before delving into the primary analysis, we conducted an evaluation of potential confounding variables, which were measured prior to the study. The statistical tests were performed using R, specifically utilizing the ggstatsplot package [281], which was also used to generate the visualizations for the analysis.

Experience with Drones For this analysis, we regrouped the two participants with no prior drone experience into the category of participants with little experience (those who had seen a drone but not used one). We then compared this newly formed group of less experienced drone interactants (N=16) with participants who were more highly experienced with drones (N=9;. i.e., all of these participants had already used a drone). The results of the Welch's t-test, with Holm-corrected p-values to account for multiple comparisons [281], indicate that experienced

Table 3.3: Mean Minimum Distance (in meters) for Each Zone, Categorized by Gender and Experience Levels with Drones and VR. Welch's t-tests revealed significant differences between males and females, as well as experienced and non-experienced individuals with VR and drones, in different zones. Significant differences are indicated by *.

		Conditions			
		Front	Front Sides	Back Sides	Back
Gender	Male (N=11)	0.67 *	0.56 *	0.57 *	0.63 *
	Female (N=12)	0.83 *	0.73 *	0.73 *	0.83 *
Drones' Experience	Little to none (N=16)	0.81	0.70	0.70	0.80 *
	Experienced (N=9)	0.67	0.58	0.58	0.66 *
VR Experience	Little to none (N=18)	0.81	0.70 *	0.70 *	0.80 *
	Experienced (N=7)	0.65	0.55 *	0.55 *	0.61 *

participants maintained a significantly closer minimum distance from the drone in the Back zone compared to their less experienced counterparts. Although large effect sizes were observed, the analyses for the Front and Front Sides zones yielded p-values just above the conventional 0.05 threshold . This outcome may be partially influenced by unbalanced sample sizes, which can reduce the statistical power of the test. Statistical power refers to the test's ability to detect a true effect; when sample sizes are unbalanced, it can lead to less reliable estimates from smaller groups. The analysis for the Back Sides zone did not reveal a statistically significant disparity.

Front	$t(20.23) = 2.06$, $p = 0.051$, $g = 0.80$, $M_{Little} = 0.81m$, $M_{Experienced} = 0.67m$
Front Sides	$t(20.04) = 2.06$, $p = 0.052$, $g = 0.80$, $M_{Little} = 0.70m$, $M_{Experienced} = 0.58m$
Back Sides	$t(19.27) = 2.00$, $p = 0.059$, $g = 0.78$, $M_{Little} = 0.70m$, $M_{Experienced} = 0.58m$
Back	$t(21.35) = 2.15$, ***p=0.042* (*)**, $g = 0.83$, $M_{Little} = 0.80m$, $M_{Experienced} = 0.66m$

The effect sizes (Hedges' g), in accordance with Cohen's (1988) conventions, ranged from moderate to large, with values between .78 and .83. The mean minimum distances (in meters) for each group are displayed in Table 3.3.

Experience with Virtual Reality In a similar fashion, we reorganized the two participants with no prior experience in Virtual Reality (VR) into the category of participants with little experience (those who have tried it once). We then compared this reconfigured group (N=18) with participants who were well-experienced in VR, having experienced it several times (N=7). The outcomes of Welch's t-test, with Holm-corrected p-values to account for multiple comparisons [281], revealed that experienced participants maintained a significantly closer minimum distance from the drone in each zone when compared to their less experienced counterparts, except for the front where the disparity was not statistically significant.

Front	$t(9.99) = 1.80$, $p = 0.10$, $g = 0.76$, $M_{Little} = 0.81m$, $M_{Experienced} = 0.65m$
Front Sides	$t(12.93) = 2.32$, ***p=0.04*** **(*)**, $g = 0.94$, $M_{Little} = 0.70m$, $M_{Experienced} = 0.55m$
Back Sides	$t(14.19) = 2.78$, ***p=0.01*** **(*)**, $g = 1.10$, $M_{Little} = 0.70m$, $M_{Experienced} = 0.55m$
Back	$t(17.61) = 3.36$, ***p=3.56e-03*** **(*)**, $g = 1.29$, $M_{Little} = 0.80m$, $M_{Experienced} = 0.61m$

The effect sizes (Hedges' g), following Cohen's (1988) conventions, were medium to large, with values ranging between .76 and 1.29. The mean minimum distances (in meters) for each group are displayed in Table 3.3.

Impact of Previous Experiences

- Individuals with **prior drone experience** chose to stand significantly closer to the drone in the Back zone compared to those less familiar with drones. While the analyses for the Front and Front Sides zones did not reach statistical significance, the observed large effect sizes and their proximity to the conventional threshold of significance suggest that this aspect merits consideration and further discussion. The potential impact of prior exposure to drones in shaping proxemic behaviors is further elaborated upon in section 3.3.5. Additionally, this variable emerged as a noteworthy differentiator among participants when examining the influence of drone digital facial emotions on proxemic behaviors (see Figure 3.3.4).
- People with multiple **experiences in Virtual Reality** (VR) tend to position themselves significantly closer to the drone than those who have only tried VR once, except in the Front zone. With large effect sizes, these findings are considered important and warrant further discussion. We explore potential explanations in the Discussion section, as detailed in section 3.3.5.
- The test of independence indicated that experience with drones and virtual reality were unrelated to each other, implying distinct impacts of both variables.

Genders Welch's t-test, conducted on 23 out of the 25 participants (excluding the two who identified as non-binary or preferred not to say), with Holm-corrected p-values to account for multiple comparisons [281], revealed that females (N=12) maintained a significantly greater minimum distance from the drone across all zones compared to males (N=11).

Front	$t(20.72) = -2.15$, ***p=0.04*** **(*)**, $g = -0.86$, $M_{Male} = 0.67m$, $M_{Female} = 0.83m$
Front Sides	$t(20.63) = -2.92$, ***p=8.27e-03*** **(*)**, $g = -1.17$, $M_{Male} = 0.56m$, $M_{Female} = 0.73m$
Back Sides	$t(20.41) = -2.86$, ***p=9.62e-3*** **(*)**, $g = -1.14$, $M_{Male} = 0.57m$, $M_{Female} = 0.73m$
Back	$t(19.68) = -3.12$, ***p=5.44e-03*** **(*)**, $g = -1.24$, $M_{Male} = 0.64m$, $M_{Female} = 0.83m$

The effect sizes (Hedges' g), in line with Cohen's (1988) conventions, were notably large (>0.8). The mean minimum distances (in meters) for each group are displayed in Table 3.3.

Independence between Previous Experiences and Gender Pearson's chi-squared test of independence was conducted across the 23 participants who identified as either male (N=11) or female (N=12). The analysis showed no significant association between gender and the level of experience with drones ($\chi^2(2) = 3.30$, $p = 0.19$) or virtual reality ($\chi^2(2) = 2.39$, $p = 0.30$). Additionally, another Pearson's chi-squared test of independence found that experience with drones and virtual reality were also independent of each other ($\chi^2(4) = 1.44$, $p = 0.84$).

Impact of Gender – Female participants maintained a significantly greater minimum distance from the drone in each zone compared to males (see section 3.3.4), showing a large effect size (Hedges' $g > .8$). While gender effects can originate from various sources, we tested for known influential variables such as experience with drones or VR. However, participants' gender was not found to be significantly associated with their level of experience with drones or VR.

Anxiety Towards Drones A Pearson correlation analysis was conducted to examine the relationship between the adapted Robot Anxiety Scale (RAS) scores and the minimum distance measured within each zone. The results revealed a statistically significant ($p < 0.05$) small positive correlation between the Discourse Anxiety subscale and the minimum distance measured within the Front ($r = 0.18$, $p = 1.86e-02$), Front Sides ($r = 0.22$, $p = 2.18e-03$), and Back Sides ($r = 0.19$, $p = 8.56e-03$) zones. However, no significant correlation was found for the Back of the drone.

Negative Attitude towards Drones A Pearson correlation analysis was also performed to investigate the relationship between the adapted Negative Attitude Towards Robots Scale (NARS) scores and the minimum distance measured within each zone. The findings are as follows:

- We identified a statistically significant ($p < 0.05$) small negative correlation between the Negative Attitudes toward Social Influence of Robots and the minimum distance measured within the Front ($r = -0.19$, $p = 6.95e-03$), Front Sides ($r = -0.18$, $p = 1.33e-02$), Back Sides ($r = -0.22$, $p = 1.26e-03$), and the Back of the drone ($r = -0.22$, $p = 1.39e-03$).

- A statistically significant ($p < 0.05$) small to moderate positive correlation was observed between the Negative Attitudes toward Situations and Interactions with Robots and the minimum distance measured within the Front ($r = 0.22$, $p = 1.43e-03$), Front Sides ($r = 0.31$, $p = 1.86e-06$), Back Sides ($r = 0.30$, $p = 6.27e-06$), and the Back of the drone ($r = 0.27$, $p = 8.99e-05$).

- A statistically significant ($p < 0.05$) small positive correlation was found between the Negative Attitudes toward Emotions in Interaction with Robots and the minimum distance measured within the Front ($r = 0.19$, $p = 6.95e-03$) and Front Sides ($r = 0.15$, $p = 4.19e-02$) zones.

The results indicate specific correlations between participants' negative attitudes toward different aspects of drone interaction and the proximity they maintained to the drone in various zones.

Impact of Prior Drone Perception

- **Anxiety** related to conversing with drones showed a small positive correlation with the maintained distance when navigating around the drone in all zones except for its back. This observation is elaborated upon in section 3.3.5.
- Increased **reluctance to drones' social influence** led to closer maintained distances when navigating around the drone. This noteworthy result is further explored in section 3.3.5.
- In contrast, negative **attitude towards social interactions** exhibited small to moderate positive correlations with the minimum distance maintained in all zones.
- Participants expressing a less favorable **attitude towards emotions** in interactions with drones maintained a greater distance from the drone, particularly within the front and front sides. This finding is further discussed in section 3.3.5.
- Though modest effect sizes were noted for each statistically significant correlation, these findings remain important within the study's context, offering insightful glimpses into the mechanisms of Human–Drone interactions and proxemic behaviors. The extensive discussions arising from these results in subsection 3.3.5 underscore their contribution to a nuanced understanding of the subject.
- Moreover, negative attitudes towards social interactions and social influence with robots emerged as notable differentiating factors among participants when exploring the impact of drone digital facial emotions on proxemic behaviors (see section 3.3.4).

Pet Ownership According to Welch's t-test, there was no statistically significant difference in the minimum maintained distance between pet owners (N=16) and non-pet owners (N=9) in any zone.

Front	$t(19.35) = -0.63$, $p = 0.53$, $g = -0.25$, $M_{Pet} = 0.75m$, $M_{NoPet} = 0.79m$
Front Sides	$t(18.04) = -0.71$, $p = 0.49$, $g = -0.28$, $M_{Pet} = 0.64m$, $M_{NoPet} = 0.69m$
Back Sides	$t(17.77) = -0.65$, $p = 0.52$, $g = -0.26$, $M_{Pet} = 0.64m$, $M_{NoPet} = 0.69m$
Back	$t(21.25) = -0.37$, $p = 0.71$, $g = -0.14$, $M_{Pet} = 0.74m$, $M_{NoPet} = 0.77m$

Manipulation Checks

After each condition, participants answer questions designed to confirm that the intended emotions have been successfully conveyed and that the two gaze behaviors (Follow/Avert) have been distinctly perceived.

Emotion Recognition As presented in the confusion matrix (see Table 3.4), the recognition rates for the facial emotions of Joy, Anger, and Sadness consistently exceeded 90%. In contrast, the recognition rates for the Surprise (76%) and Fear (54%) facial emotions were noticeably lower. Given that our study primarily investigates the influence of displayed digital facial emotions on proxemic behaviors, the accurate recognition of these expressions is of utmost importance. To ensure the precision of our analysis, we have opted to exclude from the main analysis the less-accurately recognized Surprise and Fear expressions. This decision ensures a more focused examination of the reliable and accurately recognized emotional cues.

Additionally, we calculated the recognition accuracy of individual participants to assess whether some participants performed notably poorly, which could potentially impact both their subsequent behavior and our analysis. The overall recognition accuracy was relatively high, with a mean accuracy of M=0.85 and a standard deviation of sd=0.14. However, we observed an exception with accuracy rate as low as 50%. Consequently, we are removing this particular data point for the subsequent analysis of the impact of digital facial emotions on proxemic behaviors.

Table 3.4: Confusion Matrix Illustrating the Accuracy of Emotion Recognition for Drone's Digital Facial Emotions

		Conditions				
		Joy	**Anger**	**Sad**	**Surprise**	**Fear**
Responses	**Joy**	45 (90%)	1 (2%)	0 (0%)	5 (10%)	5 (10%)
	Anger	0 (0%)	47 (94%)	0 (0%)	1 (2%)	1 (2%)
	Sad	2 (4%)	0 (0%)	47 (94%)	3 (6%)	10 (20%)
	Surprise	2 (4%)	1 (2%)	1 (2%)	38 (76%)	7 (14%)
	Fear	2 (4%)	1 (2%)	2 (4%)	3 (6%)	27 (54%)

Note: Rows indicate the choices made by participants, and columns represent displayed digital facial emotions. Correct recognitions are highlighted in green, while notable errors (>= 10%) are shaded in gray. Participants demonstrated higher accuracy in recognizing Joy, Anger, and Sadness, but encountered challenges in correctly identifying Surprise and Fear. Notably, Fear achieved only 54% accuracy and was frequently confused with Surprise (14%) and Sadness (20%).

Gaze Perception As a manipulation check, we aimed to verify the effectiveness of our designed gaze behaviors – "follow" and "avert" – in shaping participants' perception of the extent to which they felt the drone was looking at them. As detailed in section 3.3.3, the drone's gaze was conveyed through dynamic pupils' movements (see Figure 3.12), coupled with restricted drone rotations simulating head movements. A Pearson's chi-squared test of independence confirmed a statistically significant association between the drone's gaze behavior and participants' perceptions of being watched (see Figure 3.15). This validation supports the suitability of our gaze behavior variable for examining its influence on proxemic responses.

Validation of Independent Variables

- **Digital Facial Emotions –** Joy, Anger, and Sadness digital facial emotions had consistently high recognition rates above 90%, whereas Surprise (76%) and Fear (54%) were less accurately recognized (see Table 3.4). Although overall recognition accuracy was relatively high among participants (M=0.85), an outlier with a 50% accuracy rate was identified. For precision in studying the impact of displayed digital facial emotions on proxemic behaviors, less-accurately recognized Surprise and Fear expressions, along with the participant with low recognition rate, were excluded from the main proxemic analysis.

- **Gaze Behaviors –** Our manipulation check confirmed a significant association between the drone's 'follow' and 'avert' gaze behaviors and participants' perceptions of being watched (see Figure 3.15), supporting the suitability of our gaze behavior variable for examining its impact on proxemic responses.

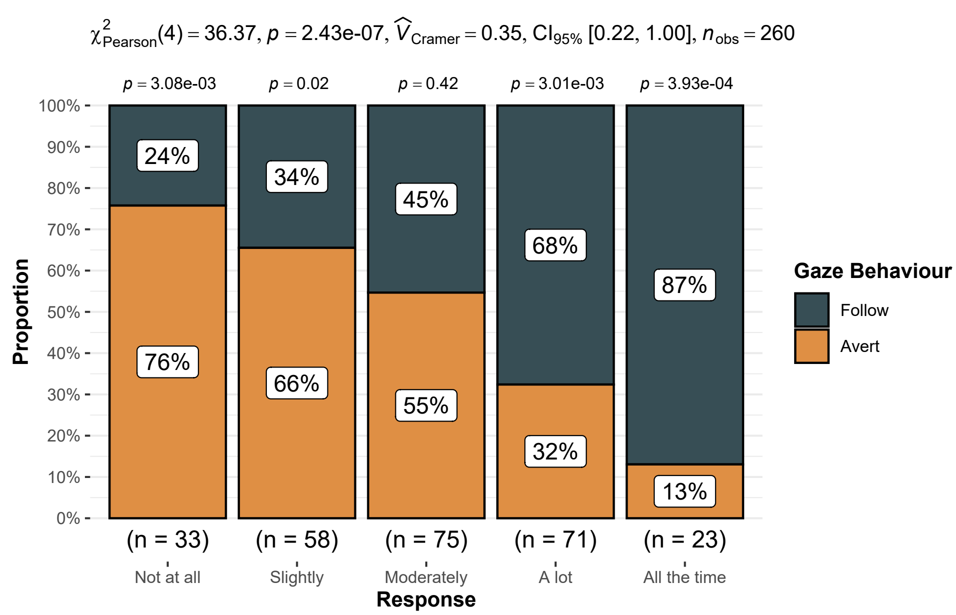


Figure 3.15: Participant's Response to "Rate the extent to which you feel the drone was looking at you." From 0 (Not at all) to 4 (All the time). A Pearson's chi-squared test of independence confirmed a statistically significant association between the drone's gaze behavior and participants' perceptions of being watched.

Proxemic Analysis

A two-way analysis of variance (ANOVA) was conducted to explore the impact of two independent variables: digital facial emotions (*Joy, Anger, Sad*) and gaze behavior (*Avert, Follow*) on the minimum distance measured during the task across four distinct zones around the drone. We assessed data for normality (Shapiro-Wilk test, p > 0.05) and verified homogeneity of variances (Levene's test, p > 0.05). Additionally, we addressed the sphericity assumption using Mauchly's test and applied the Greenhouse-Geisser sphericity correction for factors violating this assumption.

The analysis revealed a significant main effect of Gaze Behavior ($F(1,24) = 7.153, p = 0.039, ges = 0.004$) specifically in the Front zone. However, there were no significant effects of digital facial emotions, and no significant interactions between the two variables. All p-values were adjusted using the Bonferroni multiple testing correction method.

Gaze Behavior Subsequent pairwise comparisons, conducted via paired t-tests, revealed a significant difference ($t = -2.5$, $p = 0.015$, $p < 0.05$) in the mean minimum distance between the two gaze conditions in the Front zone. Participants maintained a significantly greater distance when the drone's gaze *followed* them, as opposed to when it avoided eye contact in the *Avert* condition. This finding underscores the influence of the drone's gaze behavior on participants, leading to a greater proxemic response in the Front zone.

> **Finding 1 –** When positioned in front of the drone, participants maintained a significantly greater distance when the drone's gaze followed them, in contrast to when it avoided eye contact.

Digital Facial Emotions Prior to the study, we conducted a thorough assessment of potential confounding variables, including the NARS (Negative Attitude towards Robots Scale), RAS (Robot Anxiety Scale), and participants' prior experience with drones. These factors were examined due to their potential to affect perceptions of the drone, interpretation of displayed cues, and subsequent proxemic behavior (see section 3.3.4). Although our initial analysis did not yield significant effects of digital facial emotions across the overall participant pool, we believe that exploring the data with these confounding variables in mind allows for a deeper understanding of the nuanced interactions at play, especially given that proxemic behaviors are highly sensitive to personal characteristics [163]. By considering these confounding factors, we aim to provide a richer interpretation of how digital facial emotions might influence proxemic behavior, particularly among specific subsets of participants.

- **Impact of Attitudes Towards Drones**

- **Attitude Towards Social Interaction:** The NARS Social Interaction subscale, designed to measure individuals' negative attitudes toward interacting with social robots, exhibited a significant moderate correlation with maintained distances (see section 3.3.4). We conducted Fisher's repeated measures one-way ANOVA on a subset of participants who displayed somewhat neutral or even positive attitudes toward drone interactions as indicated by NARS Social Interaction scores below -0.75 (see Figure 3.16). This analysis revealed a statistically significant difference ($F = 5.74, p = 0.009, p < 0.05$) in minimum distances in the Front zone within this subgroup (N=11), with a medium effect size ($partial\ \omega^2 = 0.02$) following Field's (2013) conventions. Subsequent post hoc pairwise t-tests disclosed that, within this subgroup, the Anger expression ($M = 0.78m$) prompted participants to maintain greater distances compared to Joy ($M = 0.73m$, $p = 0.02$) and Sad ($M = 0.71m$, $p = 0.02$) expressions. No significant effect was found in the other zones.
- **Overall Attitude Towards Drones and Social Influence:** Categorizing participants based on low or neutral NARS scores (NARS < 0.75, N = 23) yielded significant differences in Front zone proxemic responses related to digital facial emotions ($F = 3.39, p = 0.04, partial\ \omega^2 = 0.005$), with Anger ($M = 0.78m$) eliciting greater distances compared to Joy ($M = 0.74m$, $p = 0.03$). Similar categorization based on low or neutral NARS Social Influence subscale scores (NARS_SI < 0.75, N = 19) also resulted in significant differences in Front zone proxemic responses related to digital facial emotions ($F = 4.74, p = 0.01, partial\ \omega^2 = 0.007$), with Anger ($M = 0.79m$) eliciting greater distances compared to Joy ($M = 0.75m$, $p = 0.04$) and Sad ($M = 0.74$, $p = 0.04$). No significant effect was found in the other zones.

• **Previous Experience with Drones** Moreover, we observed a significant effect of digital facial emotions in the Front zone within the subgroup of participants with little to no prior experience with drones (N = 16, $F = 3.42, p = 0.04, partial\ \omega^2 = 0.007$). However, despite a higher mean distance for Anger ($M = 0.84m$), pairwise comparisons did not identify any statistically significant differences with Sad ($M = 0.80m$) or Joy ($M = 0.80m$). No significant effect was found in the other zones.

• **Other Confounding Variables** In contrast, attempts to segment participants by Gender, RAS, or VR resulted in either inadequately small sample sizes (fewer than 10 participants) or non-significant outcomes.

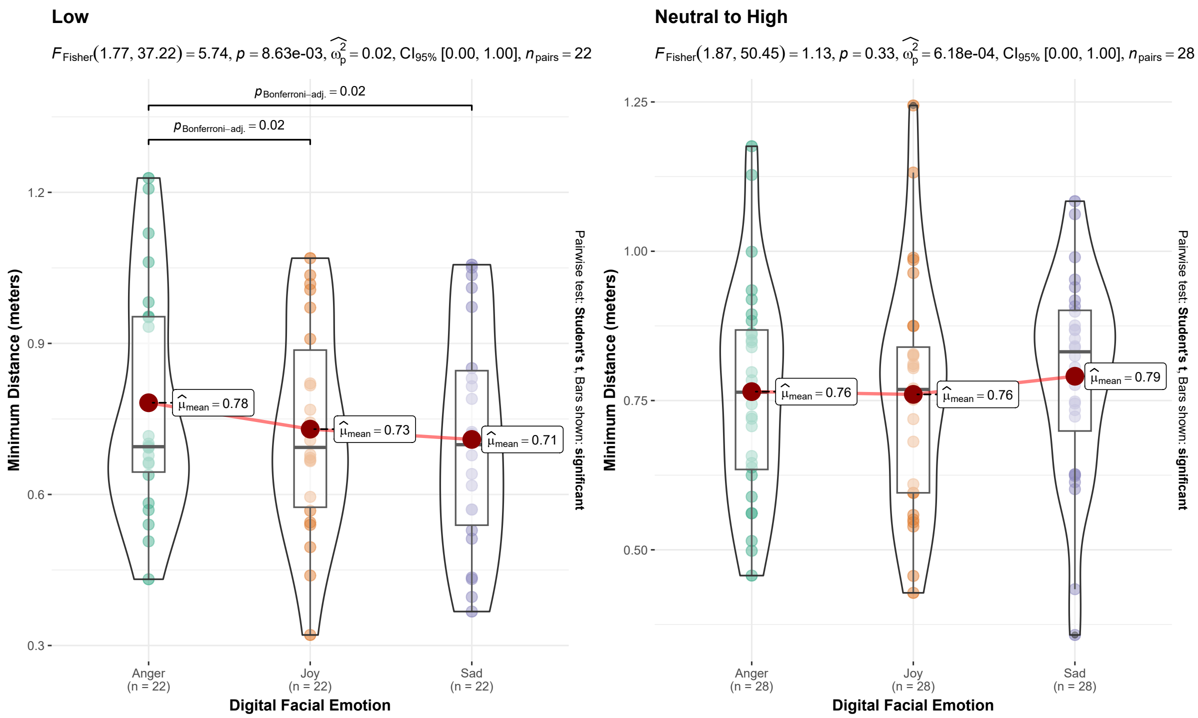


Figure 3.16: Minimum Distance by Digital Facial Emotions within the Front zone, for Low (< -.75) and Neutral to High (>= -.75) NARS Interaction Groups. Fisher's repeated measures one-way ANOVA reveals a statistically significant difference ($p < 0.05$) between digital facial emotions for the Low NARS Interaction subset.

Finding 2

- For participants with a low negative attitude towards social interactions with drones, the *Anger* expression resulted in a significantly greater distance maintained when positioned in front of the drone compared to *Joy* and *Sadness*. The digital facial emotions displayed by the drone also significantly influenced proxemic behavior in the front zone among participants with neutral to positive attitudes toward drones, their social influence, and those with little to no experience with drones.
- These results underscore the nuanced interplay of attitudes and displayed facial emotions in shaping proxemic behavior during human–drone interactions, underscoring the importance of considering individual characteristics when investigating dynamics within human–robot interactions which is discussed in section 3.3.5.

Emotion Interpretation Analysis

In this study, participants' emotional responses to the drone's displayed cues were assessed using the Self-Assessment Manikin (SAM). Additionally, participants provided Likert scale responses inspired by Herdel et al.'s coding schemes [172], to evaluate various aspects, including Affect, Empathy, Self-relevance, and Direction of the Drone's State.

To explore the main effect and interaction of the Drone's digital facial emotions and Gaze on participants' responses, we used the ARTool package on R which applies Aligned Ranks Transformation (ART) on the data, followed by a non-parametric factorial ANOVA [379]. Additionally, we conducted post-hoc pairwise comparisons with Holm adjustment using the extended ART-C procedure [112].

Self-Assessment Manikin The Self-Assessment Manikin (SAM) assesses the impact of the drone's displayed emotions on participants' emotional state along three dimensions: Arousal, Valence and Dominance.

- **Valence** Participants exhibited an overall positive emotional valence during the Joy condition (*Mdn*=7, *M*= 6.52, *SD*=1.2), while it turned negative for both the Anger (*Mdn*=5, *M*= 4.5, *SD*=1.93) and Sad (*Mdn*=5, *M*= 4.54, *SD*=1.89) conditions. We observed a significant effect of digital facial emotions on participants' emotional Valence ($F(2,120) = 34.4$, $p < 0.001$). Post-hoc comparisons revealed that the Joy digital facial emotions of the drone induced a significantly more positive emotional response ($M = 6.52$) compared to both Anger ($M = 4.50$, $p = 9.89e-11$, $p < 0.001$) and Sad ($M = 4.54$, $p = 2.42e-10$, $p < 0.001$). There were no significant effects related to the drone's Gaze, nor were there interactions between the variables.

Table 3.5: Self-Assessment Manikin (SAM) summary results.

		Follow			Avert		
		Joy	**Anger**	**Sad**	**Joy**	**Anger**	**Sad**
Valence	*M*	6.44	4.44	4.52	6.60	4.56	4.56
	SD	1.33	1.83	1.76	1.08	2.06	2.04
Arousal	*M*	3.20	3.72	3.44	2.88	3.52	3.36
	SD	1.89	2.01	1.64	1.48	1.94	2.16
Dominance	*M*	6.68	5.92	6.36	6.84	5.76	6.8
	SD	2.12	2.41	2.41	2.17	2.15	2.40

- **Arousal** Participants, on average, reported relatively low arousal levels throughout the study (*Mdn*=3, *M*=3.53, *SD*=1.85). We found no significant main effect or interaction between the Drone's digital facial emotions and Gaze behavior on participants' emotional arousal responses.

- **Dominance** The participants felt a relatively high level of dominance during their interactions with the drone (*Mdn*=7, *M*=6.39, *SD*=2.28). However, this perception of dominance was lowered when the drone displayed an Anger expression. Statistical analysis revealed a significant effect of digital facial emotions ($F(2,120) = 8.19$, $p = 0.00046$, $p < 0.005$), with Anger (Mdn=6, $M = 5.84$) inducing a significantly lower perception of dominance compared to Joy (Mdn=7, $M = 6.76$, $p = 0.00099$, $p < 0.005$) and Sad (Mdn=7, $M = 6.58$, $p = 0.0027$, $p < 0.005$).

Finding 3 – The Joy expression of the drone evoked a significantly more positive emotional response compared to both Anger and Sadness. Additionally, Anger induces a significantly lower perception of dominance compared to Joy and Sadness.

Affect To assess the extent to which the drone's cues affected participants, they provided responses to Likert scale questions related to their concerns about the drone's expressions and how much these expressions impacted their own emotions. Our results, detailed below, suggest that negative emotions, particularly Anger expressions, led to higher participant concern. The Anger expression also had a greater emotional impact when the drone maintained eye contact compared to averting its gaze.

- **Concern** On average, participants reported relatively low levels of concern (Mdn=2, M=1.79, SD=1.31), ranging between Disagreement (1) and Neutrality (2) in response to the statement that the drone's expression concerned them. The analysis revealed a significant effect of digital facial emotions on participants' concern ($F(2,120) = 20.27$, $p = 2.6e-08$, $p < 0.001$). Specifically, the Anger expression (Mdn=3, $M = 2.34$) induced significantly higher concern compared to both Joy (Mdn=1, $M = 1.12$, $p = 1.43e-08$, $p < 0.001$) and Sad (Mdn=2, $M = 1.9$, $p = 0.016$, $p < 0.05$). Sad also resulted in significantly higher concern compared to Joy ($p = 0.00035$, $p < 0.001$). Notably, there was no significant effect of the Drone's Gaze or any interaction effect, despite a slightly higher average concern in the Follow gaze condition (Mdn=2, $M = 1.89$) compared to the Avert condition (Mdn=1, $M = 1.68$).

- **Emotional Impact** Participants' subjective emotional impact was, on average, relatively low (Mdn=1, $M = 1.32$, $SD = 1.17$), with responses ranging between Slight (1) and Moderate (2) on the provided Likert scale. We found no significant main effect or interaction between the Drone's digital facial emotions and Gaze behavior. However, there was a significant effect of Gaze behavior when focusing on the Anger expression ($F(1,24) = 6.78$, $p = 0.016$, $p<0.05$). Participants perceived a significantly greater emotional impact when the drone followed them with its eyes (Mdn=2, M=1.64) compared to when it avoided eye contact (Mdn=1, M=1.16) while displaying an Anger expression.

Finding 4 – Negative emotions, particularly expressions of Anger, resulted in significantly higher participant concern. Additionally, Anger had a greater emotional impact when the drone maintained eye contact compared to averting its gaze.

Empathy To gauge participants' empathy toward the drone, they rated how much they shared the drone's emotions. On average, participants reported relatively low levels of empathy, with responses averaging around "Slight" (1) empathy (Mdn=1, M = 0.99, SD = 1.11). We observed a significant effect of the Drone's digital facial emotions on participants' empathy ($F(2,120)$ = 4.15, p = 0.018). Specifically, the Joy expression (Mdn=1, M = 1.24) led to significantly higher shared emotions compared to the Anger expression (Mdn=1, M = 0.78, p = 0.021, $p<0.05$), although the difference compared to the Sad expression (Mdn=.5, M = 0.94, p = 0.07) was not significant. Furthermore, there was no significant effect of the Drone's Gaze or any interaction effect, despite a slightly higher average empathy in the Avert gaze condition (Mdn=1, M = 1.1) compared to the Follow condition (Mdn=1, M = 0.92).

Finding 5 – Joy elicited significantly more empathy compared to Anger.

Self-Relevance To gauge the self-relevance of the displayed cues for participants, they indicated their agreement to the statement "The drone's expression showed how it felt about you." On average, participants reported relatively low levels of agreement, with responses ranging between Neutral (2) and Disagree (1) (Mdn=2, M = 1.88, SD = 0.84). We observed a significant effect of the drone's digital facial emotions ($F(2,120)$ = 4.76, p = 0.01), with Sad expressions being significantly less likely to be perceived as indicative of the drone's feelings toward the participant (Mdn=1.5, M = 1.40) when compared to Anger (Mdn=2, M = 1.86, $p = 0.0198$, $p<0.05$) and Joy (Mdn=2, M = 1.82, $p = 0.0227$, $p<0.05$). Furthermore, there was no significant effect of the Drone's Gaze or any interaction effect, despite a slightly higher average agreement in the Follow gaze condition (Mdn=2, M = 1.73) compared to the Avert condition (Mdn=2, M = 1.65).

As a follow-up question, participants were asked whether the drone's expression was more likely due to something in the environment. Again, their responses ranged between Disagree (1) and Neutral (2) (Mdn=2, M= 1.88, SD = 0.84). We haven't found any effect or interaction of digital facial emotions or Gaze Behavior.

Finding 6 – The Sad expression significantly conveyed less about how the drone felt toward individuals compared to expressions of Joy and Anger.

Direction of the Drone's State We examined whether participants believed that the drone's state signaled a potential future action or intent, rather than being a consequence of a past event. On average, participants' responses ranged from "Disagree" to "Neutral" for both Anger (Mdn=2, M = 1.7, SD = 1.13) and Sad (Mdn=1, M = 1.42, SD = 1.09), and from "Neutral" (2) to "Agree" (3) for Joy (Mdn=2, M = 2.20, SD = 1.12). A significant effect of the drone's digital facial emotions emerged ($F(2,120) = 10.46$, $p = 6.51e-05$, $p < 0.001$), with Joy being significantly more associated with intent compared to Anger ($p = 0.0097$, $p < 0.001$) and Sad ($p = 4.41e-05$, $p < 0.001$). Furthermore, there was no significant effect of the Drone's Gaze or any interaction effect, despite a slightly higher average agreement in the Follow gaze condition (Mdn=2, M = 1.81) compared to the Avert condition (Mdn=2, M = 1.73).

Finding 7 – Joy exhibits a significantly stronger association with the intent of future actions compared to Anger and Sadness.

3.3.5 Discussion

Social Proxemic Function in HDI

In the realm of Human–Drone Interaction (HDI), understanding how individuals manage their spatial relationships with respect to drones is paramount for the successful integration of drones into human social spaces. While social mechanisms have been identified as significant drivers of proxemic behaviors in people's interactions with ground humanoid robots [263], it cannot be assumed that the same principles automatically apply to HDI [5, 107]. Existing research tends to cast doubt on the role of the social proxemic function in HDI, with some researchers attributing this limited role to the highly mechanized nature of drones, which may hinder the establishment of social perceptions [58, 227]. Our study delved into this topic by investigating proxemic behaviors when interacting with a drone that displays social cues in the form of a digital face with different emotional expressions and gaze behavior.

Role of the Social Function Our research explored the influence of social cues, primarily the drone's gaze, on individuals' proxemic behavior. Notably, participants consistently maintained a significantly greater distance from the drone when it made eye contact, as opposed to when it averted its gaze. This phenomenon mirrors behaviors observed in both human–human interactions [8, 24, 31] and human–robot interactions [263], suggesting a certain degree of transferability of proxemic norms from these contexts to human–drone interactions. One possible explanation for this, in line with findings by Mumm et al. [263] regarding ground robots, is the equilibrium model of proxemics [11, 24]. This model posits that individuals regulate intimacy through physical distance: as increased eye contact leads to greater perceived intimacy, it triggers a distancing response to maintain a comfortable level of closeness, while reduced eye contact can conversely prompt individuals to approach.

Another possible explanation lies in the functional role of gaze in communication, as it provides feedback on the other party's attention and reactions [24]. If individuals perceive the drone is actively paying attention to them via eye contact, they may feel no need to approach further to engage discussion. However, when the drone averts its gaze, participants might be compelled to get closer until they gain the drone's attention, much like in human interactions where people move closer to establish a connection through shared gaze. When proxemic behaviors are viewed as goal-oriented, participants may interpret the drone's gaze as sufficient confirmation that it is aware of them, maintaining their distance to perform their task. In contrast, when eye contact is absent, they may believe they need to reduce the distance to ensure the drone receives their intended communication. This highlights the potential for drones to use gaze cues to signal attention, a concept worth exploring in future research.

Despite the low subjective significance and reported influence of the drone's digital facial emotions, our study revealed a statistically significant impact of these expressions on proxemic behaviors, particularly within specific participant subgroups. Interestingly, expressions of anger led to greater distancing, followed by joy and sadness. These patterns align with observations in human–human interactions [298, 319] and human–robot interactions [43]. Anger expressions tend to evoke avoidance behaviors, joy expressions encourage approach behaviors, and sadness lead to a combination of automatic approach tendencies with conscious withdrawal [319]. Notably, the impact of digital emotional faces was most pronounced among two specific groups: individuals with positive or neutral attitudes toward robots and those with limited to no prior experience with drones. This highlights the nuanced nature of proxemic behaviors and their sensitivity to individual differences and past experiences, which we explore further below (see section 3.3.5).

Moreover, the discrepancy between subjective perceptions of social cues and actual behavioral observations underscores the importance of studying human-drone interactions through natural and unobtrusive methods, such as the interactional methods employed in this study (see section 2.2), rather than relying solely on surveys. As suggested by Seidel et al. [319], initial automatic responses to social visual stimuli may be followed by a more conscious and complex re-evaluation, influenced by factors like familiarity with the entity and personality traits. This differentiation between controlled and automatic processes in interpersonal behavior offers valuable insights into the mechanisms of social interaction in HDI.

Context-Dependent Significance Both the gaze behavior and digital facial emotions of the drone played pivotal roles in shaping the spatial dynamics of the interaction, indicating the presence of a social proxemic function, at least in specific contexts. Importantly, the social influence and its significant effect manifest within the front zone of the drone. This front zone corresponds to the area where participants initially engage in conversation with the drone. However, this social function becomes less prominent as participants shift their focus from social engagement to task-oriented actions, such as reaching for information located behind the drone (see Figure 3.9).

In this new context, the drone's role appears to transition from a social entity to something more akin to an obstacle. In line with this, we observed that within the front zone where participant engage conversation with the drone, there is a significant positive correlation between maintained distance and participants' anxiety related to conversing drones. Yet this correlation disappears in the back zone. This transition suggests a potential situational change in participants' mindset, from engaging in a discussion activity to simple navigation. Furthermore, the negative attitude towards drone emotions only exerted a significant impact on proxemic behaviors within the front and front sides zones, corresponding to areas where participants are directly exposed to emotional displays. This observation might indicate a physical distancing response triggered by these cues, which dissipates once the emotional displays are no longer in view. These findings emphasize the dynamic and context-dependent nature of proxemic behaviors, enhancing our understanding of human–drone proxemics within social spaces.

In summary, our research sheds light on the social proxemic function in HDI, unveiling its existence and its susceptibility to contextual shifts and individual differences. It indicates a potential for drones to tailor their design and behavior to suit specific individuals and situations. To leverage these insights, designers should consider creating drones that can adapt their social cues based on the context of the interaction. For example, drones could utilize more expressive emotional displays during social engagement while minimizing these cues during task-oriented activities. Furthermore, providing user-customizable settings for emotional expression could allow individuals to adjust the drone's behavior to match their comfort levels and preferences (e.g. amount of eye-contact), ultimately fostering a more personalized interaction experience.

Attitudes and Framing in Human–Drone Interaction

Our study's examination of specific participant subgroups provides valuable insights into how unique interpretations of social cues affect proxemic behaviors. Firstly, our findings indicate that individuals who exhibit open and accepting attitudes toward human–drone interactions tend to be more responsive to emotional cues presented by a drone. These individuals' favorable disposition toward robot interactions appears to heighten their receptiveness to the emotional signals conveyed by the drone. Interestingly, prior research has recognized the Negative Attitude Toward Robots Scale (NARS) score as a significant predictor of individuals' reactions to and interpretation of cues from drones, including their flying movements [42]. Consistent with this finding, our study revealed that participants with higher reluctance toward drones' social influence tended to maintain closer distances when navigating around the drone. Their resistance to the drone's social influence may have influenced their behaviors, preventing a social interpretation of displayed cues and framing the drone more as an object and obstacle. This, in turn, impacted the resulting proxemic behaviors, akin to maintaining a closer distance from a mannequin (object) than from an actual individual. Researchers could delve deeper into this phenomenon to explore the intricate relationship between negative attitudes towards robots (whether as measured by the NARS questionnare or other means) and individuals' interpretation of social cues generated by robots.

Secondly, our findings shed light on the impact of participants' previous exposure to similar technologies. Notably, individuals with limited familiarity with drones displayed a heightened sensitivity to the emotional cues presented. It underscores the concept of "framing", which plays a crucial role in the interpretation of cues within human–robot interactions [58,91,95,180]. Framing, in the context of human–drone interactions, refers to the mental framework or perspective through which individuals interpret their interactions with drones and the cues presented. When individuals lack an established frame of reference for interpreting perceived cues, they often adopt a frame that aligns with their previous experiences and beliefs [117]. Experienced drone users, accustomed to considering drones as technical devices for specific purposes, tend to frame their interactions as primarily technical and non-social. They may perceive the cues displayed by the drone as functional or non-social signals. In contrast, those with limited experience may readily adopt a frame of interpretation more akin to human–human interactions. Their previous experiences have accustomed them to perceiving and responding to facial expressions and emotional cues in a social context. As a result, when interacting with drones, they might frame these cues as social signals.

This observation carries significant implications for the design and implementation of drones in various contexts. It suggests that when developing drones for users who are either open to robot interactions or relatively new to drone technology, the incorporation of expressive facial features can be a valuable component. Such features might enhance the interaction experience and foster more positive attitudes and engagement.

Stimulus Significance

On the whole, participants did not establish a strong connection between the drone's expressions and what the drone thought of them or their surrounding environment. The consistently low ratings on various Likert scales suggest that participants may have perceived the drone's expressions as relatively context-neutral and abstract, lacking specific relevance to the interaction context. As outlined by Bradley [51], detecting stimulus change does not always elicit significant responses, and the task-relevance of the stimulus, referred to as its "significance", affects the magnitude of the response. While participants easily recognized these expressions, the ability of these cues to convey nuanced emotional content or context-specific messages seemed limited. This contrasts with findings from Herdel et al. [172], where individuals interpreted the drone's emotions beyond mere recognition, creating narratives around the drone's state. This indicates that the interpretation of cues is sensitive to the context in which they are presented, highlighting the importance of context for the transferability of studies examining the impact of drones' social cues.

Beyond the relevance of the displayed social behaviors, it is important to recognize that the context in which these behaviors occur can lead to varied interpretations and reactions from individuals. As we strive to integrate these social cues to improve interactions in practical applications, future research should investigate how the context surrounding these cues shapes their significance, influences their interpretation, and ultimately affects individuals' behavioral responses.

Virtual Reality to Examine Future Drones

In our study, we employed Virtual Reality (VR) as an experimental platform to observe participants' natural behaviors within an immersive, safe, and replicable environment during interactions with an innovative drone design. VR has become an established tool for similar research purposes, with an increasing volume of data and theoretically-grounded studies that enable researchers to gain confidence in their findings and better anticipate the limitations of their results.

Transformed Interaction Compared to previous virtual studies investigating human–drone proxemics, our work embraces the full potential that VR offers and present a transformed interaction rather than true-to-life simulation [306]. Indeed, both the drone's sound and airflow can elicit physiological excitement and, according to the arousal regulation proxemic function [122, 282], may cause individuals to distance themselves from the drone, influencing our results. While minimizing sound and excluding airflow limit the generalizability of our findings (given that these elements are typically integral to current drone designs and influence proxemics [59, 122]), they also allow for the observation of subtle social adaptations that might be obscured by proxemic responses to these stimuli. VR effectively removes uncontrollable aspects present in real-world settings, creating a unique but close to real experience. Although this may hinder the transferability of findings, acknowledging these limitations ensures transparency and allows for external evaluation of the findings' applicability, while also offering insights relevant to the design of future drone technologies. Nonetheless, this work would benefit from replication in real-world settings to assess its transferability and to gain a deeper understanding of how sound and airflow can influence a drone's social impact on users.

Innovative Design Furthermore, we introduced an innovative drone design, which, while feasible in real-world settings, has been demonstrated as presenting challenges (e.g., flight stability), as observed in similar attempts [389]. This study not only contributes valuable insights to our understanding of human–drone interaction within VR but also lays a solid foundation for future investigations in the field that seek to harness VR for similar purposes.

Unexpected Effects Despite efforts to minimize behavior alterations in VR, a significant factor emerged: participants with prior VR experience approached the drone more closely than those without. This suggests that individual characteristics notably influence proxemic behaviors. Possible explanations include a greater comfort level with advanced technology or enhanced motor capabilities. Previous studies indicate that less capable individuals tend to maintain greater distances [17,128]. Although all participants had equal opportunities to navigate the virtual environment, inexperienced users may have felt hesitant to move freely, possibly fearing collisions with virtual objects. In contrast, experienced users likely had a clearer understanding of VR's capabilities, fostering greater confidence in their navigation. While addressing these subjective perceptions is complex, future research should investigate the factors influencing individuals' perceived ability to navigate virtual environments.

3.3.6 Conclusion

In summary, our research has highlighted important consequences of social cues on the spatial dynamics of Human–Drone Interactions. Drones, characterized by their mechanical and task-oriented nature and operating in the air, present a unique challenge in seamlessly integrating into social contexts. The transformative potential of social cues for increasing these machines' social acceptance is only just beginning to be explored. Leveraging the flexibility of Virtual Reality (VR), our study has created a controlled and adaptable environment where 25 participants engaged with drones displaying a range of facial expressions and gaze behaviors.

Our study represents a significant contribution to the field of Social Drones and human–drone interactions, with a specific emphasis on the social proxemic function. Within our VR environment, participants exhibited behaviors that resonated with established Human to Human interaction norms. They maintained greater distances when the drone made eye contact and approached closer when the drone averted its gaze, thereby revealing the existence of a social proxemic function in HDI. Additionally, the drone's facial emotion display generated different proxemic responses from participants, with Anger leading to greater distancing, followed by Joy and Sadness. These patterns align with observations in Human–Human and Human–Robot interactions. Nontheless, the impact of emotional facial expressions was only significant among two specific participant groups: individuals with positive or neutral attitudes toward robots and those with limited to no prior experience with drones. This emphasizes the sensitivity of proxemic behaviors to individual differences and past experiences.

Additionally, it is crucial to acknowledge the study's limitations. While conducted within a controlled VR environment, the observed behaviors may not fully represent real-world scenarios. The influence of individuals' VR experience on their subsequent behaviors remains to be investigated. Furthermore, participants' subjective ratings suggest that they perceived the drone's expressions as relatively context-neutral and abstract, lacking specific relevance to the interaction context. Although our study observed automatic behavioral responses to these cues, it is essential to explore the more conscious and nuanced interpretation, as it holds potential for conveying meaningful messages. Hence, further research could delve into the contextual significance of these social cues, providing a better understanding of their practical uses and relevance in real-world human–drone interactions.

In conclusion, our work reveals factors influencing the social proxemic function during HDI. It offers valuable insights into the impact of the drones' gaze and emotional face during Human–Drone Interactions, emphasizing the role of individual participant characteristics, attitudes, and past experiences in shaping people's proxemic behaviors in relation to the drone. As we navigate the evolving era of autonomous drones, understanding and refining the role of social cues to foster harmonious coexistence between drones and humans is crucial.

3.4 Chapter Conclusion

This chapter investigated the communicative proxemic function in Human-Drone Interaction (HDI), defined as the socially driven spatial adjustments, proactively exhibited as communication cues, or aimed at regulating spatial appropriateness in response to external social influences from the drone. Although this function is often considered the default in proxemic studies due to its extensive use in human-human and human-robot interactions (i.e., Hall's framework), its relevance in human-drone interactions is debated [227] and misunderstood. The function relies on the unverified and questionable assumptions that autonomous drones are perceived as social entities and that proxemic behaviors around them are socially-driven. Therefore, a detailed examination was necessary to determine its actual role in explaining human-drone proxemics and to critically evaluate the assumptions underlying its application.

We leveraged the unique advantages of virtual reality (VR) to overcome the constraints of real-world studies, maximizing ecological validity by following guidelines derived from a synthesis of literature on proxemics and VR (see section 2.3.2) and a real-world/VR comparison study presented in chapter 4. This enabled us to conduct unobtrusive proxemic studies, observing and accurately measuring natural spatial behaviors using interactional methods in safe, controlled, and realistic environments. We selected specific variables based on current research in Human-Drone Interaction (HDI) and their established effects in human-human and human-robot interactions. This approach allowed us to contribute to the HDI field while examining the communicative proxemic function. By setting expectations according to Hall's frameworks, we aimed to determine whether our empirical findings align with existing research or offer new insights requiring further investigation [264]. In addition to proximate explanations, this search for ultimate explanations through comparing and discussing our results with multiple proxemic theories not only helped us evaluate the role of the communicative proxemic function but also uncovered potential influences from other determinants, such as goal-oriented, protective, and arousal regulation mechanisms, which are further explored in subsequent chapters.

Our first study demonstrated that the social dimension of human-drone interactions and the resulting proxemic behaviors is not predominant with today's drones, notably due to their mechanical design. However, our initial findings suggest a promising design space where drones could evolve beyond being mere autonomous objects evolving in inhabited environments, as defined by Baytas et al. [38], to become true social entities that would engage users at a higher level, triggering social mechanisms that enhance user engagement, well-being, and interaction with enhanced interaction capabilities.

Our second study provided a preliminary demonstration of the potential social influence exerted by drones. The findings indicate that people respond to social cues displayed by drones in a manner similar to their responses to humans and humanoid robots. By leveraging virtual reality, we were able to extract more detailed metrics, revealing that the relevance of the social dimension may be context-dependent. For instance, social behaviors are more predominant when engaging in a conversation, whereas individuals navigating through a crowd tend to perceive others as obstacles. Interestingly, our results suggest that people responded intuitively to social cues from drones without perceiving them as social agents. This finding underscores the subtle social influence drones may exert, distinguishing between two key assumptions: 1) that autonomous drones are perceived as social entities (not verified in our study, but potentially possible in contexts where the social dimension is significant, the drone's design facilitates social influence, and individual traits are compatible), and 2) that people's proxemic behaviors around drones are driven by social factors (partially verified).

3.4.1 **Research Question 1.1 –** What is the role of the Communicative Proxemic Function in HDI?

The Role of The Communicative Function

Ultimately, the role of the communicative proxemic function and its relevance for motivating investigation, predicting, or interpreting results cannot be assumed but must be assessed on a case-by-case basis. Our work demonstrates that with typical drones available today, the lack of social elements in their overall design, the irrelevance of the social dimension in indirect interaction situations (e.g., passing by), and the way people initially perceive them (e.g., as technological objects rather than social entities), render the communicative proxemic function irrelevant in explaining proxemic behaviors around them. However, when modifying these parameters by implementing social components in the drone, such as a digital face, and emphasizing the social dimension through a socially contextual interaction (i.e., engaging in a conversation), the communicative proxemic function becomes more relevant. Our results suggest that people's proxemic behavior can be socially driven, influenced by the drone's social cues, and mirroring behaviors expected among humans.

Similar to how VR creates an illusion of reality and triggers natural reactions from users to the stimuli presented, autonomous drones can create the illusion of being social entities and activate social mechanisms. However, just as a low plausibility illusion can undermine the virtual experience in VR, a lack of meaningful and coherent social elements in drones can diminish their ability to exert strong social influence. Our studies revealed that a mere social framing without sustained social components created a dissonance that disrupted the potential social connection anticipated by participants. Additionally, participants perceived the drone's expressions as relatively context-neutral and abstract, which limited their ability to convey nuanced emotional content or context-specific messages, resulting in only minor, unconscious social influences. Therefore, the social experience should be holistic and integrated, similar to everyday social interactions which are rich, multimodal, and deeply embedded in concrete interactions.

Future research could explore several avenues to enhance the social potential of drones. This includes developing more context-aware social cues that can adapt to the specific interaction environment and user needs. Investigating the integration of multimodal communication—such as combining visual, auditory, and behavioral cues—could create a richer and more engaging social experience. Additionally, exploring the impact of continuous social interactions over time, rather than isolated instances, may provide deeper insights into how drones can build sustained social connections.

Individual Differences

Both studies underscore the significant differences among individuals in terms of drone perception and proxemic behaviors. Notably, they reveal the importance of individual frames, which are structures that can increase or decrease the relevance of different aspects of a situation. Frames can be either pre-existing, stemming from people's previous experiences, personal beliefs, and opinions, or produced by specific contexts or intervention (as seen in the study). This influence aligns with the context-dependent relevance of the social dimension, where participants shift from a social frame when engaging in a conversation with the drone and focusing on its face, to a neutral/obstacle frame, where the drone becomes an object they must circumvent to reach their objective. Additionally, dissonance between individual and produced frames might have detrimental effects. Therefore, when designing drones and conducting studies, it is crucial to consider what frame individuals might adopt or what frame is (intentionally or not) produced by the experimental setting or specific interaction context, as this can shape the way people will perceive the situation and the drone, and their resulting behaviors.

Should It Be Social?

Leveraging humans' natural tendency to perceive non-human entities as social beings offers significant potential. However, the variability in individual preferences and the unpredictability of responses to these artificially social entities pose important considerations. In some contexts, it may be more practical and beneficial for these entities to be perceived simply as objects rather than social agents. For example, adding a face to a mechanical robot arm in a factory might not provide substantial value and even induce distancing behaviours. It's important to recognize that the social design space is a spectrum, with varying degrees of social influence required based on the context. Social mechanisms can be used to provide intuitive communication, such as indicating directions, with minimal emotional engagement. Conversely, emotional engagement can be beneficial in situations like search and rescue operations, where it helps reduce stress and supports the rescue process, or in emotional support drones where a stronger social connection can be useful. Ultimately, drones should be designed to adapt their level of social influence according to their specific purpose and user needs. This approach ensures that the design maximizes both operational efficiency and user well-being by tailoring the social elements to the context in which the drone operates.

3.4.2 Contribution to Research Question 1.5 – How do multiple proxemic functions interact in HDI?

Other Proxemic Functions

While our studies primarily focused on the communicative proxemic function, we remained aware that other driving mechanisms might influence people's proxemics. Notably, we explained the impact of the drone's flying altitude using the defensive proxemic function. Participants tended to get closer to the drone when it was above them because they perceived more available space to react to potential danger. Previous research has shown that drones can be perceived as potential threats, suggesting a role for the defensive proxemic function in human-drone interactions. However, this has not been thoroughly examined or considered as a theoretical framework for explaining human-drone proxemics. We delve into the role of the defensive proxemic function in HDI in chapter 4.

Additionally, in study 1, the task at hand significantly influenced some participants' behaviors, diverting their attention from the drone and possibly leading to a decreased perception of danger. In study 2, participants may have interpret the drone's gaze from a goal-oriented rather than social, with eye-contact indicating mutual attention, and no need to get closer to engage conversation, while they may be tempted to approach the drone to catch its attention when it isn't looking at them. This suggests that the nature of the task and how participants experience it can drive behavior and shape their perception of the drone and the situation. As drones will interact with people performing various tasks, it is crucial to better understand the role of goal-oriented behaviors in human-drone proxemics and their interaction with other proxemic functions. This is explored in chapter 5.

Moreover, in our previous works and the first study, drone noise was reported as a significant source of annoyance, with some participants moving away for this reason. This hints at a potential arousal regulation function of proxemic behaviors, which has not yet been examined in HDI. Chapter 6 specifically focuses on unveiling this function and understanding its role in human-drone proxemics.

Ultimately, multiple proxemic functions might be active simultaneously, creating a dynamic interplay of approach and avoidance forces that result in a single proxemic outcome. Chapter 7 synthesizes the findings from previous chapters to present a comprehensive model of human spatial dynamics, describing the processes through which proxemic behaviors emerge in relation to external entities, including social drones.

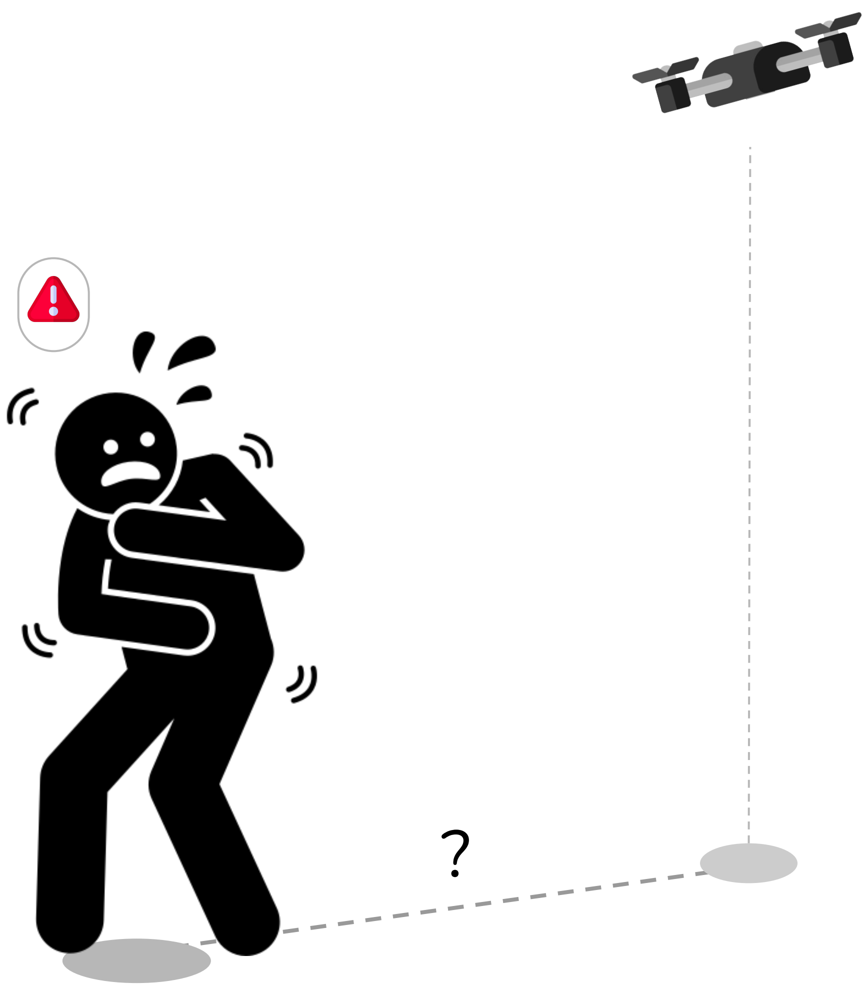
3.4.3 **Contribution to Research Question 2 –** How best to use VR to study human-drone proxemics?

Virtual Reality

Recognizing the many constraints of real-world proxemic studies, we turned to virtual reality (VR) as a promising alternative. Our initial research led to the creation of guidelines based on a combined literature review of proxemics and VR concepts, detailed in chapter 2. In our immersive virtual environments, participants exhibited natural spatial behavior around a drone, allowing us to observe subtle and unconscious adaptations that previous studies missed, such as the impact of flying altitude on proxemics. While Study 1 could have been conducted in a real-world setting, Study 2, which involved implementing a dynamic digital face on a flying drone, went beyond current technological capabilities. This demonstrates VR's potential to expand the drone design spectrum and provide research opportunities that real-world studies cannot offer. However, in our first study, we observed that some participants did not perceive the potential harm from colliding with the drone, raising concerns about how virtual environments might alter the perception of drone-related threats. While studies have shown that various physical and psychological threats can be effectively induced in VR, it remained unclear whether people would perceive a virtual drone as equally threatening as a real one. Beyond potential differences in perception, it was crucial to determine if the trends in threat perception evolved similarly, allowing the discovery of similar phenomena in VR, potentially of lesser magnitude but still valuable for research. While this issue may be less critical when investigating social phenomena, as we did in this chapter, it becomes crucial when exploring defensive behaviors around drones. To address this concern, we conducted a study focusing on the role of the protective proxemic function in HDI within both a real environment and its virtual replica. This involved comparing direct measures and findings, as well as gathering participant feedback. This study is presented in chapter 4 alongside the examination of the protective proxemic function.

Chapter 4

The Defensive Proxemic Function



4.1 Chapter Introduction

Defensive proxemics refers to how individuals use physical space to protect themselves from perceived threats. It is part of a broader process in which people assess their environment [48, 115, 133] and adopt defensive strategies to effectively manage perceived risks [44]. Central to this process is cognitive appraisal, the mental evaluation individuals perform when encountering a potential threat, such as a drone. This involves two key stages: primary appraisal, where they assess the level of danger, uncertainty, or demand posed by the situation, and secondary appraisal, where they evaluate their ability to cope with it. These assessments shape their defensive responses, including the use of spatial distancing as a safety buffer to maintain the threat at a manageable level, allowing for escape or readjustment if necessary. Since cognitive appraisal is highly sensitive to individual differences, such as past experiences, personality traits, and available resources, the perception of threat and corresponding stress levels vary widely among individuals [48, 115, 133]. The intensity of perceived risk influences the degree of spatial adjustment, and when distancing is insufficient or no longer viable, individuals may engage other defensive mechanisms to regulate stress and manage the situation [44].

4.1.1 Motivation

Why Assessing the Defensive Proxemic Function? Drones are often perceived as potential threats to both physical safety and privacy [82]. If individuals perceive drones as threats, their presence could lead to stressful environments and provoke defensive behaviors, such as maintaining greater distances [96, 103] or even aggressive reactions like attacking the drones [45]. Such responses could hinder the social acceptance and effective deployment of drones. Given these perceptions, the defensive proxemic function seems a promising framework for explaining people's spatial and other defensive behaviors around drones, although it remains largely unverified. The detrimental effects of this dynamic are still hypothetical, as this aspect of human–drone interaction is poorly understood and understudied. There is limited insight into how individuals perceive, react to, and are impacted by the threats drones may pose.

Building on theories that underpin defensive behaviors, such as Cognitive Appraisal [48,133] and Defensive Behaviors [44, 45], this research aims to assess whether participant responses align with these theoretical predictions, thereby validating their relevance for understanding behavior around drones [264]. This exploration will enhance our understanding of human–drone proxemics, and the spatial strategies employed to mitigate perceived threats [103].

While chapter 3 evaluated the significance of a well-established proxemic function in Human-Drone Interaction (HDI), this chapter seeks to introduce and apply relevant theories from other fields that are not yet widely adopted in HDI research. This shift from assessing established concepts to exploring new, potentially transformative theories aims to broaden our understanding of human behavior in the context of drones.

The insights gathered will help researchers better address these issues and explore ways to mitigate negative effects, such as stress or defensive responses. Additionally, a deeper understanding of human–drone proxemics can inform the design of proxemic-aware social drones [156] that adapt their behaviors to enhance user comfort and reduce defensive reactions. If our findings contradict existing theories, they will still offer valuable insights and identify areas for further investigation and refinement.

4.1.2 Overview of the Study #3: *"Assessing Defensive Proxemics in Human-Drone Interaction: Real vs. Virtual Environments"*

Motivation To address the potential negative impacts of drones' presence and evaluate whether theories like Cognitive Appraisal [48,133] and Defensive Behaviors [44,45] apply to human–drone interactions, this study investigates how various drone states (e.g., approaching, hovering) and parameters (e.g., speed, distance) influence people's perceived stress and discomfort. Specifically, the goal is to explore the relationship between these factors and perceived threat levels. We address the following research question, with the associated hypothesis presented in subsection 4.3.1:

- **RQ1:** Do individuals' psychological responses to different drone states (e.g., approaching, hovering) align with expected behaviors related to perceived threats?

This will provide the first empirical evidence of how a drone's presence and dynamic behaviors affect users, enabling better predictions of their effects in social settings and identifying strategies to mitigate these impacts through appropriate drone behavior.

Studying natural human responses to drones, particularly in terms of threat perception and defensive behaviors, is challenging due to the risks drones can pose and the limitations of real-world experiments. Safety measures in these settings, such as transparent barriers or cables, often distort participants' threat perceptions and behaviors. Virtual Reality (VR) offers a compelling alternative, allowing for safe, controlled environments that simulate real-world interactions without physical risk [382]. However, just as safety precautions may affect real-world behavior, the inherent safety of VR could influence how participants perceive threats. This raises a key question, with the associated hypothesis presented in subsection 4.3.1:

- **RQ2:** Do people perceive and respond to drones in Virtual Reality (VR) similarly to how they do in real-world environments, particularly regarding threat perception?

Given the limited research validating VR for studying human–drone interactions from a defensive perspective, this study also aims to determine whether the findings from virtual environments align with those from real-world settings, ensuring the reliability of VR for such research.

Study Design & Methodology This chapter presents a comparative study involving 42 participants, conducted in both real-world and Virtual Reality (VR) environments. The study had two primary objectives: 1) to assess how different drone states (e.g., approaching, hovering) influence participants' perceived stress, discomfort, and their relationship with perceived threat levels, and 2) to evaluate how responses to drones differ between real and virtual environments. Specifically, we examined whether virtual drones could evoke threat perceptions and responses similar to those caused by real drones.

The study took place in a real-world setting and its VR replica, with drones moving at two distinct speeds (1 m/s and 0.25 m/s). Participants' perceived stress was measured during a resting baseline and across different drone states (static far, approach, static close). Additionally, their discomfort levels and preferences regarding drone proximity were recorded. After each speed condition, participants rated the perceived threat level of the drone. Semi-structured interviews were also conducted to explore participants' expectations for real-world scenarios beyond the laboratory, the factors influencing their threat perceptions, and how their behaviors might differ between real and virtual environments.

Results The results highlight the potential negative impacts of drones on people's well-being in social spaces. Participants' reactions during passive drone interactions were consistent with defensive behaviors typically triggered by perceived threats. Stress levels increased in direct correlation with the perceived risk posed by the drone, and this rise in stress was strongly linked to the intensity of the drone's perceived threat. Significant variations in stress were observed depending on the drone's state and proximity to participants. Notably, drones moving away from personal space significantly reduced discomfort, while both discomfort and stress levels were positively correlated with the perceived threat posed by the drone.

The consistency of these findings across both real and virtual environments suggests that VR is a valid platform for studying human–drone interactions, provided that key factors are accurately replicated in the simulation.

Semi-structured interviews revealed several factors that influenced participants' perceptions of threat, including drone sound, unpredictability, the presence of propellers and cameras, proximity, and movement patterns. These insights offer important starting points for developing strategies to address and reduce the perception of threat. Overall, the study underscores that drones can present significant challenges to people's comfort and safety in social settings, raising important questions about the readiness of drones for widespread use in such contexts. We propose guidelines for future research aimed at advancing the development of safe, trustworthy, and socially acceptable drones.

4.1.3 Chapter Structure

The structure of this chapter follows the format of the paper from which it originates [59]. It begins with a related work section that provides a tailored synthesis of relevant theories, HDI research, and the use of VR concerning defensive behaviors and threat perception. This overview equips readers with the necessary insights to understand our research approach and results. Next, we present the methodology employed to address this research gap, emphasizing a highly controlled environment essential for performing the study in a real-world setting and enabling the desired comparison with the virtual setting. Following this, we present the quantitative and qualitative results, continuing with multiple discussion points. The chapter concludes with a summary that encapsulates the objectives and main findings of our research. Following this summary, we provide detailed responses to RQ 1.2, "What is the role of the Defensive Proxemic Function in HDI?" based on the findings. Additionally, we offer partial answers to RQ 2, "How can VR be effectively used to study human-drone proxemics?" and RQ 1.5, "How do multiple proxemic functions interact in HDI?"

4.2 Related Work

This section provides a synthesis of relevant theories, HDI research, and the use of VR concerning defensive behaviors and threat perception. A comprehensive literature review of general proxemics, including human–drone proxemics and virtual reality, is presented in chapter 2. In contrast, this section narrows its scope to focus specifically on studies and related work that are directly relevant to the current investigation and the particular proxemic function under examination.

4.2.1 Defensive Space

Dosey and Meisels [11, 103] described personal space as a "buffer zone" to serve as protection against perceived emotional, physical, or privacy-related threats. Similarly, another space-related concept, peripersonal space (PPS; defined as reaching space around the body) is associated with a "safety margin" [309] around the body. PPS is very flexible [243] and its representation relies on individual-specific integration of salient sensory inputs in a given situation. Orientation of threatening objects [86], their approach [65, 360], acute stress [113] and personality (e.g., anxiety [309, 337]) are known factors of PPS. Other theories related to defensive behaviours and stressful encounters describe the detection, proximity and intensity of a perceived threat as triggering specific behaviours (Risk Assessment [44, 45] and Cognitive appraisal [48, 133]). Unlike previous Human–Drone proxemic studies, we will build on these theories to drive the explanation of our results.

4.2.2 Human–Drone Proxemics and Threat Perception

Proxemics has been identified as a critical design concern for social drones [38]. Wojciechowska et al. [382] showed that participants' preferred a straight front moderately fast (0.5m/s) approach, with a drone stopping in the personal space (1.2m). Yet they did not report on whether drone's approaches affected individuals' stress level or threat perception. Reflecting on people's reactions to drone collision, Zhu et al. [391] found that the drone's unpredictability, propeller sound and degree of protection all influenced perceived threat in a crashing situation. They mentioned that less threatened participants were more comfortable with closer drone distances. Whether threat has been induced by the crashing situation or the drone per se remains unclear. Their results are therefore limited in that they investigate participant's perception during a crashing situation and cannot be generalized to more common interactions and drone's behaviours. Abtahi et al. [4] showed that a safe-to-touch drone induced significantly closer distance and more engaging interactions compared to a control drone. While it shows that the drone's design impact user's overall perception and safety feeling, it doesn't say much about how the drone's behaviour dynamically affect people. Auda et al. [27] report safety as a main participant's concern for drone body landing . Contrarily, exploring natural human–drone interactions, Cauchard et al. [76] report few safety concerns amongst participants. They found the drone's noise and wind are linked to the participants' discomfort level and longer preferred distances from the drone. In light of these results, it remains unclear whether perceived threat or other components (drone's sound, wind) are responsible for people preferred distances and discomfort.

Our work aims to elucidate this phenomenon through a theoretically informed examination of how a drone's presence, approach, and proximity affect individuals' stress, discomfort, and threat perception. By examining participants' experiences with a drone approaching at two different speeds and hovering at various locations, we assess whether these dynamic aspects of drone behavior significantly impact well-being using a child-friendly consumer drone. Additionally, we evaluate the relevance of established theories on stress and threat management to better understand human responses to drones perceived as potential threats.

4.2.3 Virtual Reality as a Methodological Tool

While a growing body of literature has begun to examine human factors during human–drone collocated interactions, some researchers [58, 107, 235] have pointed out the potential impact of safety techniques on peoples' reactions near drones (e.g., minimum distance [5, 107, 164], transparent wall [164], fixed drone [107, 389], or fake drone [82]). In parallel, Virtual reality is a relatively novel yet promising approach for the HDI field. It is safe, reproducible, and moderately realistic [382]. It has been used to investigate human drone proxemics for co-existing context [58], body landing [27], path planning algorithm for in-home monitoring [40] and novel drones' shapes [77]. However, these benefits are contingent upon VR's ability to evoke natural reactions from participants in response to the stimuli presented. In particular, we wonder whether a virtual drone can affect people in a similar way as a real one, in terms of induced stress, threat and discomfort.

Virtual environments have been widely utilized in Social Psychology [306], Human–Computer Interaction (HCI) [88, 248, 265], and Human–Robot Interaction (HRI) [307, 377]. Research has shown that VR can effectively simulate stressful situations and evoke instinctive defensive responses [33, 303, 305], demonstrating its potential to elicit natural reactions to drone-related threats within a virtual environment. However, participants' responses can vary based on their experience of the virtual environment and their sense of presence, which is influenced by factors such as Place and Plausibility Illusions [330], Presence [93], and Embodiment [139, 366]. The study aims to maximize immersion to enhance presence and evaluate whether interactions with a drone in a highly immersive virtual environment yield similar observations to those in a real-world setting. Given that presence can vary significantly among individuals [99, 280], it is challenging to predict but can be measured [283, 315, 326].

Existing Comparisons Kamide et al. [197] compared proxemic preferences and impressions of a humanoid ground robot in real and virtual environments and found no significant differences in terms of desired space, despite varying subjective impressions. Conversely, Li et al. [230] observed inconsistent proxemic preferences between live and VR ground robots, with no major changes across different VR settings. These mixed results, coupled with the lack of theory-driven explanations, create uncertainty about the validity of VR for Human–Robot proxemic studies. Additionally, drones differ significantly from ground robots, as suggested by a previous comparison [5]. This implies that the mechanisms driving proxemic behavior may vary between ground and flying robots, highlighting the need for different considerations when using VR for proxemic experiments involving drones. In this chapter, we focus on evaluating the validity of studying defensive proxemic behaviors within immersive virtual environments. This approach is significant because defensive proxemics has been identified as a potential factor influencing people's behavior around drones, as discussed in chapter 3. However, the behavior of some participants also raised concerns about whether a virtual drone would evoke the same threat perception and reactions as a real one.

To evaluate how the perception of a virtual drone from a defensive perspective—and its impact on people's reactions—differs between virtual and real-world settings, we compared a real-world experimental environment with its virtual counterpart. In both settings, participants were approached by a drone at two different speeds, with the drone stopping at their intimate boundary. We measured and compared participants' stress, discomfort, perceived threat levels and qualitative feedback across both environments.

4.3 Methodology

This study aims to investigate two key aspects: 1) how different drone states (e.g., approaching, hovering) affect participants' perceived stress, discomfort, and their relationship with perceived threat levels, and 2) how responses to drones differ between real and virtual settings. To achieve this, we compared participants' perceived stress during a resting baseline and under various drone flying conditions (static far, approaching, and static close) for two speed conditions (1 m/s and 0.25 m/s). We assessed participants' perception of the drone's threat level after each speed condition to determine if the drone's state, proximity (close or far), and speed affect perceived stress and threat. This approach helps identify whether a flying drone induces stress and if its state, proximity, and speed modulate this stress, while also exploring the relationship between induced stress and perceived threat.

Additionally, participants underwent a modified stop-distancing procedure (see subsection 4.3.2), where they rated their discomfort and assessed the ideal drone position at various distances (from 40 cm to 450 cm from the participant). This approach helps us understand proxemic preferences and how discomfort varies with distance. Although the intimate zone margin [163] is typically 45 cm, we positioned the drone slightly closer (40 cm) to explore its impact on perceived discomfort more thoroughly.

Participants were divided into two groups: one experienced the real-world setting, while the other interacted with a virtual replica. This division allows us to evaluate how the environment influences perceived stress, discomfort, and distance ratings, and to compare the results across real and virtual settings to assess consistency.

All manipulations, measures, sample size justification, and main hypotheses were pre-registered on the Open Science Framework (OSF) before data collection: https://osf.io/utas4. We report all manipulations and measures in the study, in line with recent proposals [138].

4.3.1 Experimental Design and Hypotheses

This study is structured into two main blocks: Block (A) and Block (B). Block (A) examines the impact of various human-drone interaction (HDI) scenarios on participants' perceived stress and its correlation with the perceived threat level of the drone. Block (B) evaluates proxemic preferences using a modified stop-distancing procedure, where participants' perceptions of the stopping distance required after the drone has approached at a specific speed are assessed. Each block is conducted twice, once for each speed condition ($1m/s$ or $0.25m/s$), and each is tested either in a real or virtual environment. Block (A), which involves observing the drone's speed, precedes Block (B) to ensure that participants have context for the speed when evaluating their proxemic preferences in Block (B).

Block (A) follows a 2x2x4 mixed split-plot design with the *Environment* (Real, VR) as a between-participant factor, the drone's *Speed* (1 m/s, 0.25 m/s) as a within-participant factor, and the *Phase* (Baseline, Static Far, Approach, Static Close) as a four-level within-participant factor. The dependent variable is the self-reported stress for each phase and condition. The drone's threat level is also assessed for each condition. If the drone is perceived as a potential threat, we expect the participant's perceived stress to evolve as the situational threat changes from a static distant threat to an approaching (looming) threat, and finally to a static close threat. Our specific hypotheses are:

H0: Participants' perceived stress will differ significantly across the phases, with the approaching phase being the most stressful due to danger ambiguity (unknown stop distance) and instinctive responses to looming objects [45, 360]. This is followed by the static close threat (within PPS), the static distant threat, and finally the resting baseline.

Looming objects (i.e., approaching drones) trigger specific defensive responses that are influenced by the perceived threat and the object's approach speed [360]. Thus, we hypothesize:

H1: Perceived stress will be significantly higher when the drone approaches at 1 m/s compared to 0.25 m/s.

H2: Reported threat levels will be positively associated with perceived stress.

Given the effort to develop a highly immersive virtual environment that replicates the critical elements of the real-world scenario, we expect the illusion of reality to be strong enough to enable the following hypothesis:

H3: The previous hypotheses will hold in both environments. However, due to the reduced perceived danger in VR, we expect perceived stress to be significantly lower in the virtual environment compared to the real world.

Block (B) follows a 2x2x6 mixed split-plot design with as input variables the *Speed*, *Environment* and the six-level within-participant variable *Stop_distance* (C0: Intimate Space (40cm), C1: 83cm, C2: Personal Space (120cm), C3: 240cm, C4: Social Space (360cm), C5: 450cm). The stop distance starts near the intimate space's frontier (where the drone stops its approach) and then reaches half of the personal space, its frontier, half of the social space, its frontier, and finally the maximum distance allowed by the experimental setting which is within the public space. Hall's framework [163] is extensively used in human–drone proxemics [164, 235, 382], using these scales allows other researchers to more easily compare their results with ours. We aim to map people's personal space via the measure of their discomfort level and distance ratings (too close or too far from their ideal distance).

H4: We expect the discomfort level to be significantly higher at the intimate frontier (PPS) compared to the other conditions.

H5: We expect the discomfort level to be positively associated with the perceived threat level.

The speed conditions' order was randomized using a Latin square.

4.3.2 Measures

Self-Reported Stress For each phase, participants verbally rated their perceived stress on a scale from 0 (no stress at all) to 5 (moderate stress) to 10 (extreme stress), a method validated by Shiban et al. (2016) [323].

Threat Level After each speed condition, participants rated how threatening they perceived the drone to be on a scale from 0 (not threatening at all) to 5 (moderately threatening) to 10 (extremely threatening).

Stop Distance and Discomfort Ratings After each condition, we conducted a distancing procedure. The drone, initially positioned at the intimate frontier, moved back incrementally five times. Based on Hall's framework [163], the drone's stop positions corresponded to intimate space (40 cm), half of the personal space (83 cm), the personal space limit (120 cm), half of the social space (240 cm), the social space limit (360 cm), and the public space (maximum distance of 450 cm). For each stop position, we asked participants, "How ideal is the drone stop position, from -100 (Too close) to 0 (ideal stop distance) to 100 (Too far)? A negative number indicates that you consider the drone to have stopped too close, with higher negative values reflecting greater intensity. Conversely, a positive number means you think it is too far. A rating close to zero means the drone is near what you consider its ideal stop position." Additionally, participants verbally estimated their level of discomfort, responding to, "How much do you rate your level of discomfort on a scale from 0 (no discomfort at all) to 100 (maximum discomfort)? 50 is moderate discomfort. The higher you rate, the more discomfort you feel." A similar rating has already been used in previous experiments [374].

Questionnaires Before the experiment, participants completed a demographics questionnaire (age, gender, prior experience with drones and virtual reality, reluctance about drones' safety), the Big Five Inventory (BFI) – 10 (measuring the five personality dimensions: extraversion, agreeableness, conscientiousness, neuroticism, openness) [296], the Fear of Pain Questionnaire (FPQ) – 9 (measuring fear and anxiety associated with pain) [250], and the State-Trait Anxiety Inventory (STAI) [338]. Each questionnaire was utilized to assess potential confounding factors. Previous research has shown that trait anxiety, personality traits (such as neuroticism), and fear of pain can impact defensive distances [284, 309, 337] or perceived risks in a situation [158]. The questionnaires were created using FormR and completed on the experimenter's computer in the lab. Participants in the VR group additionally completed the Igroup Presence Questionnaire (assessing presence) [315], the Avatar Embodiment Questionnaire [283], and a plausibility questionnaire [326].

Semi-directed Interview After the experiment, we conducted semi-structured interviews to delve into participants' threat perception, coping or defensive strategies, and experiences with VR. Using an affinity diagram [245], we identified patterns and themes in their responses. We transcribed the interviews and initially categorized the responses by first-degree similarity (e.g., specific drone components, virtual environment characteristics, or behaviors). These responses were then regrouped by overarching concepts (e.g., safety, appeal, annoyance) to develop deeper insights.

Post-experiment semi-directed interviews were then conducted focusing on threat perception, coping or defensive strategy, and VR. We used an affinity diagram [245] to find patterns and themes in participants' responses. To develop the insights, we transcribed the interviews, and categorized responses by first-degree similarity (e.g., same drone's component, virtual environment characteristics or behaviours), then regrouped responses by concept (e.g., safety, appeal, annoyance).

4.3.3 Setup and Apparatus

Drone Programming For the real-world condition, we programmed a DJI Tello (98 x 92.5 x 41 mm) on Python using the DJI Tello SDK. Connected by Wi-Fi to the experimenter's computer, the drone executes the commands such as taking off and moving forward for X distance at Y speed allowing us to accurately predict its stop distance. The drone's accuracy relies on optical flow. We optimized the environment by ensuring suitable lighting and using the drone manufacturer's mission pads which serve as identifiable surface patterns that guide the drone. Relying on this accuracy and fixing the initial participant-drone distance (450cm), we can move

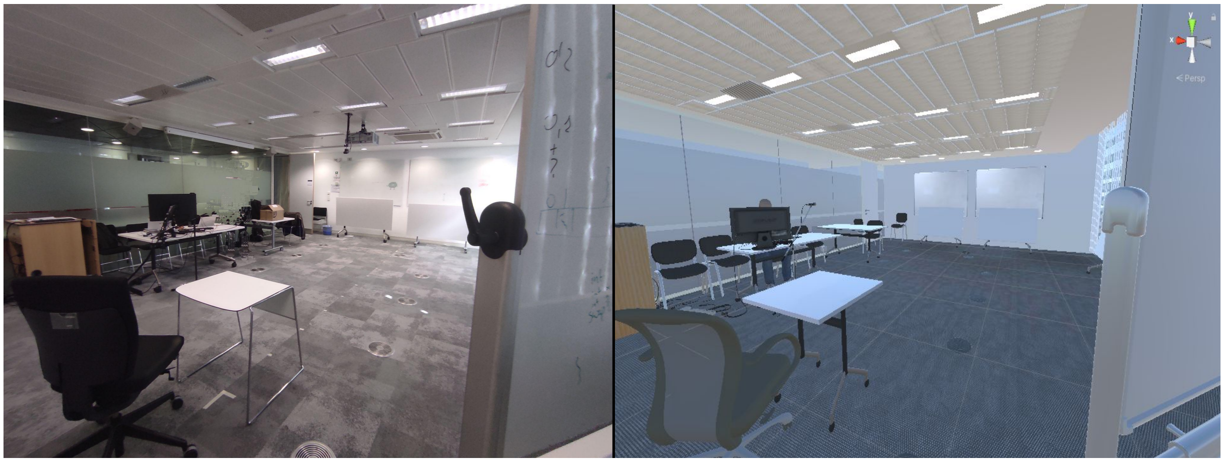


Figure 4.1: Experimental Room (left) and its replica created in Unity 3D (right).

the drone to a specific proxemic area (e.g., personal space - 120cm, intimate space - 40cm). The experimenter manually set the drone's height to match the eye level per participant. The drone is partially autonomous in that it follows a pre-programmed algorithm but the experimenter still has control via the computer. The DJI Tello has been used in recent HDI experiments [143,150].

Virtual Environment This study employs the experimental setup described in section 2.3.2. Participants wore a Meta Quest 2 (see Figure 4.1).The Unity project is available on the Thesis GitHub repository [56].

Ecological Validity The general challenges associated with using VR for proxemic studies (i.e. distance compression), along with the solutions implemented in our experimental setup, are discussed in section 2.3.2. Distances, drone's characteristics (appearance, sound, and behavior), room's dimensions and arrangement, and avatars' position (participant and experimenter) have been carefully reproduced to limit the alteration of potential confounding factors in participants' evaluation of the situation (risk assessment [45] or cognitive appraisal [133]). The spatial audio we used relies on a high-quality drone recording [375], and the size replicate the real drone's size. We animated the virtual drone to show the rotating propellers, and imitate hovering imperfections (e.g., shakes).

4.3.4 Participants

We recruited 42 participants (17 male, 24 female, and one non-binary), mainly undergraduate and postgraduate students from scientific backgrounds (Computing Science, Psychology, Veterinary), between 21 to 42 years old (M=26.69, SD=4.98). Participants were mainly from Europe (15), North America (20), with smaller representations from Latin America (2), the Middle East (4), and Africa (1). Regarding VR experience, 8 participants reported no experience, 21 had little experience, 9 were well-experienced, and 4 were very experienced. For drone experience, 1 participant had no experience, 34 had little experience, 7 were well-experienced, and none were very experienced. We randomly assigned each participant to one of the two groups (Real-world/VR), aiming to maximize gender parity and maintain a similar group size. The research received ethical approval from the University of Glasgow Ethics Committee (reference number: 300210260).

4.3.5 Protocol

After welcoming the participant to the experimental room, we invited them to fill in the consent form and read the participant protocol. The protocol stated we wish to test a feature of our autonomous drone called the "face-detection approach" and study how people feel about it. They were told the drone will move toward them two times and stop once it detects their face, but did not know the stop distance. We additionally warned them that malfunctioning can happen. They were allowed to move away if they thought they had to or if we asked them to avoid the drone. The VR group wore the Meta Quest 2 and was immersed in a replica of the experimental room. The rest of the experiment was similar for both groups (see Figure 4.2). Participants were asked to rate their stress level (0-no stress at all to 10-maximum stress) during each phase and how threatening the drone was (0-not threatening at all to 10-extremely threatening) after each condition. After the experiment, the VR group answered VR-related questionnaires (IPQ [315], Plausibility questionnaire [326], AEQ [283]). We finally performed a semi-directed interview aiming to better understand the process through which they rated their stress and threat level. The VR group shared their impression of the virtual environment while the real-world group described what would be important to make them feel and behave the same if the experiment was performed in VR. We also explored their behaviours in the case of a malfunctioning drone or a similar situation outside of the experimental context.

4.3.6 Limitations

While this study provides valuable and novel insights into HDI proxemics and people's well being around drones, the generalizability of its results is limited in that they have been obtained in a given context (indoor, sitting on a chair, in presence of the experimenter) for a specific task (face detection approach) and drone and they might significantly differ from other settings. Moreover, while self-reported stress measures are widely used and valuable indicators, they provide only limited information on physiological stress reactivity and biological outcomes compared to measures such as heart rate and skin conductance, and participants may be hesitant or unable to accurately report their true stress levels. Another issue is that the drone slightly moved in the real environment condition due to limitations in hardware and the sensors responsible for balancing the drone. This may have had an impact on participants. This is not an issue in VR, though, as the drone's movements were fully controlled.

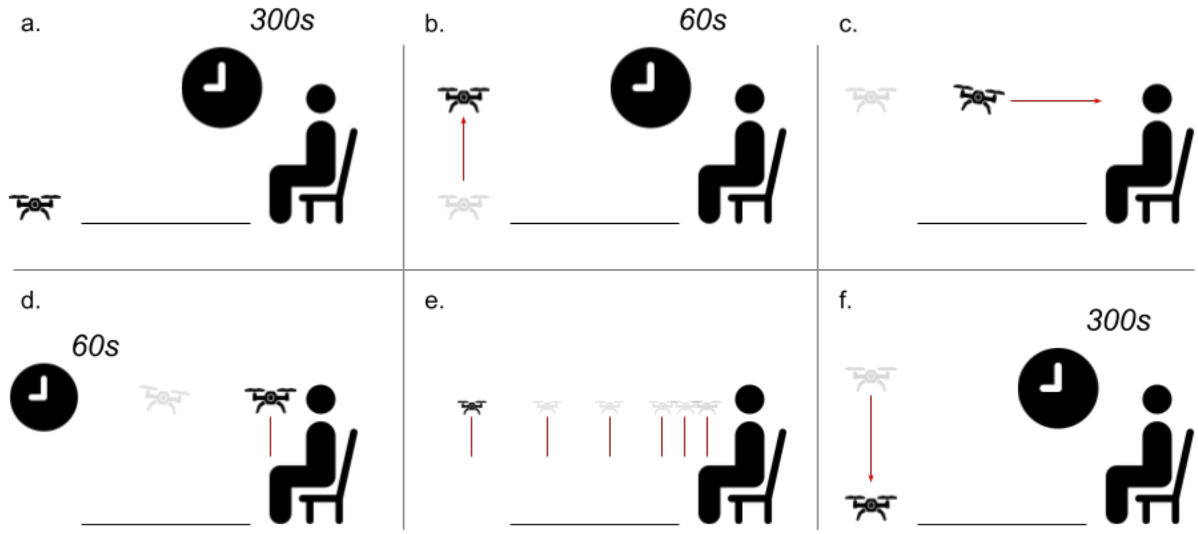


Figure 4.2: Overview of the protocol. a) Resting baseline (300s): The drone is on the ground at 450cm from the participant. b) The drone takes off and remains stationary for 60s. c) "Face detection approach": the drone approaches the participant at the target speed condition (0.25 or 1 m/s) and stops at the intimate frontier (40cm). d) Static Close: It stays in front of the participant for 60s. e) Distancing procedure: Stop distance and discomfort ratings for 6 predefined drone positions. f) Resting period: The drone lands and rests for 300s. Then the protocol resets to step b for the second speed condition.

4.4 Results

The subsequent section presents a detailed analysis of the results and statistical tests. Summary tables, which include a direct comparison between real-world and VR measures, can be found in the appendix (see Appendix section B).

4.4.1 Perceived Stress

The study showed that the different phases of the drone's flight had a significant effect on participants' perceived stress, with the Approach phase being the most stressful. However, there was no significant difference in stress levels between fast (1m/s) and slow (0.25m/s) approaches. Additionally, the study found that participants' perceived threat was found to be strongly correlated with their perceived stress. These findings were consistent in both the real and virtual environments, with no statistically significant difference between them.

Phase (Significant) A Friedman test was run for each Environment group to determine if there were differences in perceived stress between Phases. Pairwise comparisons were performed with a Bonferroni correction for multiple comparisons. There was a statistically significant impact of the phases on perceived stress, in the real ($\chi^2(4)=51.14$, $p < .0001$) and virtual environment ($\chi^2(4)=53.07$, $p < .0001$).

In VR, post hoc analysis revealed statistically significant differences in perceived stress between the Baseline ($Md = 1.17$) and the other phases except the resting period: Static Far ($Md = 2.64, p = 0.025$), Approach ($Md = 4.5, p = 0.003$), Static Close ($Md = 4.14, p = 0.005$). The Approach was also significantly different than the Static Far ($p = 0.028$), and the Resting ($p = 0.003$) and the Static Close significantly differed from the Static Far ($p = 0.044$) and the Resting ($p = 0.003$).

In the real environment, the perceived stress was statistically significantly different between the Approach ($Md = 4.37$) and each of the other phases: Baseline ($Md = 1.35, p = 0.0009$), Static Far ($Md = 1.89, p = 0.0006$), Static Close ($Md = 3.39, p = 0.028$), Resting ($Md = 1.52, p = 0.0006$). The Static Close was also significantly different than the Resting ($p = 0.015$).

Speed (No statistically significant difference) A Wilcoxon signed-rank test was conducted for each *Environment* group to determine the effect of *Speed* on perceived stress during the drone's approach. In both environments, there was a median decrease in perceived stress between the approach at 1 m/s ($Md_{Real} = 4.67, Md_{VR} = 4.61$) compared to 0.25m/s ($Md_{Real} = 3.95, Md_{VR} = 4.39$), but this difference was not statistically significant in the real environment ($z = 32.5, p = .121$) and in VR ($z = 36, p = .83$).

Environment (No statistically significant difference) A Kruskal-Wallis H test was conducted to determine if there were differences in perceived stress between groups that performed the experiment in a real environment (N=23) or in a virtual replica (N=18). Distributions of perceived stress were similar for both groups, as assessed by visual inspection of a boxplot. Perceived stress scores increased from the Real ($Md = 2.5$), to the VR group ($Md = 2.79$), but the differences were not statistically significant, $\chi^2(1) = 0.000691$, p = 0.979.

Threat Relationship (Significant) In both environments, Kendall's tau-b correlation was run to assess the relationship between threat level and perceived stress during the flying phases (see Figure 4.3). Preliminary analysis showed the relationship to be monotonic. There was a statistically significant, strong positive correlation between these two variables in the real ($\tau(41) = .56, p < .0005.$) and virtual environment ($\tau(34) = .64, p < 0.0005$).

4.4.2 Proxemics

The study showed that the distance at which the drone stopped had a significant effect on participants' discomfort, with the closest stop distance being the most uncomfortable. Additionally, the study found that participants' pre-threat assessment was strongly correlated with both their discomfort and distance ratings. However, there was no significant difference in discomfort levels between the different speed conditions. These findings were consistent in both the real and virtual environments, with no statistically significant difference between them.

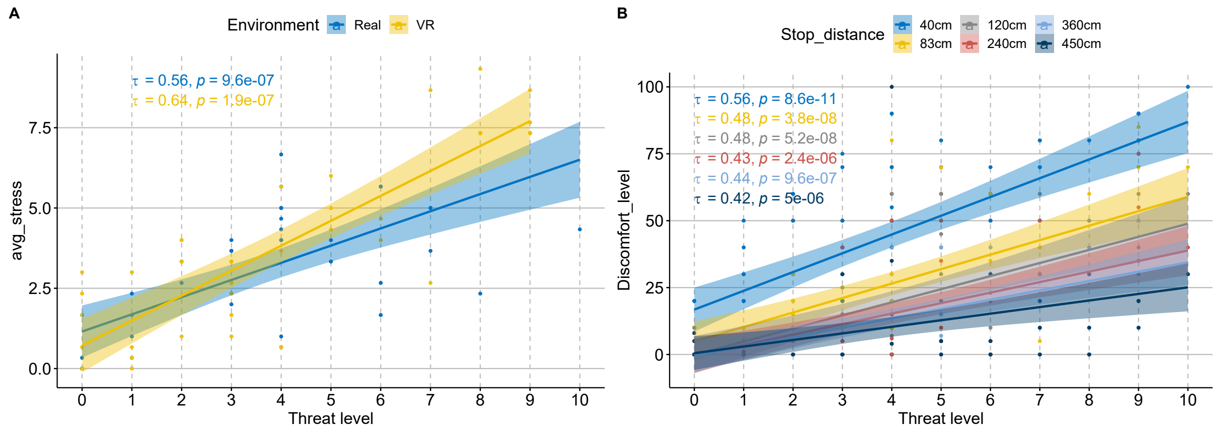


Figure 4.3: **A** A Kendall's tau-b test revealed a significant strong positive correlation between the drone's threat level and perceived stress during the flying phases in the real ($\tau = 0.58, p < 0.05$) and virtual ($\tau = 0.64, p < 0.05$) environments. **B** Kendall's tau-b correlation tests revealed a significantly strong correlation between the reported drone's threat level and participants' discomfort for each stop distance. We however notice a decrease in the correlation strength when leaving the intimate space (40cm).

Stop Distance (Significant) A Friedman test was run for each Environment group to determine if there were differences in discomfort and distance ratings between Stop distances. Pairwise comparisons were performed with a Bonferroni correction for multiple comparisons. There was a statistically significant impact of the stop distances on **discomfort level**, in the real (χ^2(5)=70.46, p < .0001) and virtual environment (χ^2(5)=65.42, p < .0001). **In the real** environment, post hoc analysis revealed statistically significant differences in discomfort between the intimate space (40cm)($Md = 41.3$) and the other conditions ($Md(83cm) = 20.6, Md(120cm) = 13.5, Md(240cm) = 9.81, Md(360cm) = 8.49, Md(450cm) = 6.9$). The condition 83cm was also significantly different than Personal Space (120cm). **In VR**, both the intimate space (40cm) (Md=47.2) and the 83cm (Md=32.3) conditions were statistically significantly different compared to the other conditions ($Md(120cm) = 25.5 < Md(240cm) = 20.9 < Md(360cm) = 19 < Md(450cm) = 14$). There was a statistically significant impact of the stop distance on **distance ratings**, in the real (χ^2(5)=104.46, p < .0001) and virtual environment (χ^2(5)=89.08, p < .0001). **In the real** environment, post hoc analysis revealed statistically significant differences in distance rating between each conditions ($Md(40cm) = -52 < Md(83cm) = -19.1 < Md(120cm) = -3.57 < Md(240cm) = 15.1 < Md(360cm) = 31.8 < Md(450cm) = 46.4$) **In VR**, each condition was also statistically significantly different to the others ($Md(40cm) = -54.4 < Md(83cm) = -25.5 < Md(120cm) = -10.4 < Md(240cm) = 13.1 < Md(360cm) = 35.5 < Md(450cm) = 55.2$).

Speed (No statistically significant difference) A Wilcoxon signed-rank test was conducted for each Environment group to determine the effect of Speed on discomfort level and distance rating. **In VR**, there was a median decrease in discomfort ($Md(0.25) = 25.5 < Md(1) = 27.6$)

and a median increase in distance rating ($Md(0.25) = 2.4 > Md(1) = 2.36$) between 0.25m/s compared to 1 m/s, but these differences were not statistically significant (Discomfort: $z = 30.5, p = .311$, Distance rating: $z = 63, p = .53$). **In the real** environment, there was a median increase in discomfort ($Md(0.25) = 18.7 > Md(1) = 15$) and a median decrease in distance rating ($Md(0.25) = -2.51 < Md(1) = 8.22$) between 0.25m/s compared to 1 m/s, but these differences were not statistically significant (Discomfort: $z = 99.5, p = .0.556$, Distance rating:$z = 54.5, p = 0.0619$).

Environment (No statistically significant difference) A Kruskal-Wallis H test was conducted to determine if there were differences in discomfort or distance ratings between groups that performed the experiment in a real environment (N=23) or a virtual replica (N=18). Distributions were similar for both groups, as assessed by visual inspection of a boxplot. Distance ratings increased from the VR ($Md = 2.38$), to Real group ($Md = 2.92$), and discomfort decreased from the VR ($Md = 26.5$) to the Real group ($Md = 16.8$), but the differences were not statistically significant, (Discomfort: $\chi^2(1)$ = 1.04, p = 0.308. Distance ratings: $\chi^2(1)$ = 0.0118, p = 0.913).

Threat Relationship (Significant) In both environments, Kendall's tau-b correlation was run for each stop condition to assess the relationship between threat level and discomfort level. Preliminary analysis showed the relationship to be monotonic. There was a statistically significant, strong positive correlation between these two variables as shown on Figure 4.3.

4.4.3 Qualitative Results & Guidelines

After the experiment, we ran semi-directed interviews to unveil the factors contributing to perceived danger of drones, explore participants' defensive behaviours and examine the potential impact of VR on these aspects. We present the main themes from our affinity diagrams, with participant responses annotated (P + participant ID) and "VR" for virtual group participants.

How to Decrease the (Perceived) Danger?

Based on our discussions with participants regarding the drone's perceived dangerousness in this experiment, we outline high-level guidelines to reduce the drone's threat level and enhance acceptability of proximity.

1) Positive associations: Beyond its loudness, the drone's sound and design are negatively connoted in participants' minds. (P1) said "this drone looks a little bit like a huge insect", (P41-VR) "it looks like a military thing". (P33-VR) said "It's like, constantly like a mosquito" and (P18) "Like something chop your head." Although it is hard to predict what associations might emerge in people's minds, fostering positive ones may orient participants' framing [312] towards an optimistic interpretation of the situation. Modifying the nature of the sound or the drone's

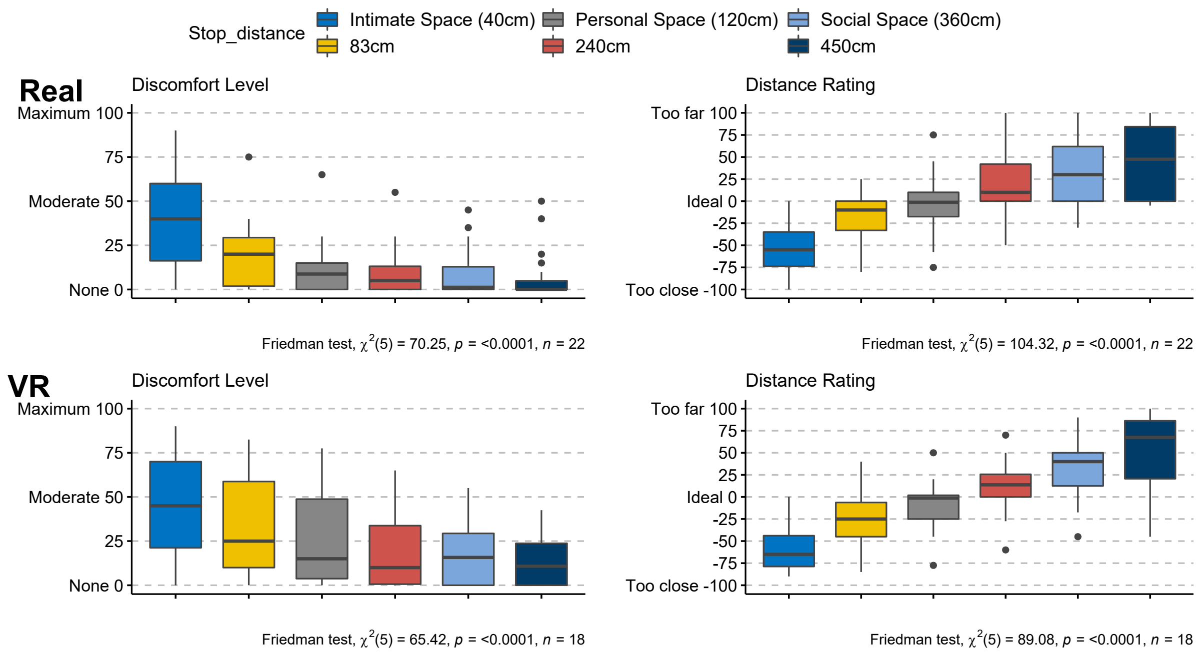


Figure 4.4: Discomfort level (left) and stop-distance ratings (right) in the real (top) and virtual (bottom) environments for each stop condition. Friedman tests revealed a statistically significant effect of the drone stop distance on participants' discomfort and distance rating in both environments. We can observe an increase in discomfort when entering the personal space (below 120 cm). Overall, the personal space frontier (120cm) was rated the closest to participants' ideal distance (rating of 0) in the real ($Md = -3.570$) and virtual environment ($Md = -10$).

design ((P15) "maybe like birds", (P3) "have some cute sticker" or (P13) "bright colours") could help. Wojciechowska et al. [382] have investigated the multifaceted people's perception of existing drones' design, Yeh et al. [389] showed that using a round shape and displaying a face helped decrease personal space, and Cauchard et al. [77] have found that radical drone forms strongly affect the perception of drones and their interactive role.

2) Communicate its intention: As in previous work [391], the unpredictability of the drone was reported as an important source of perceived danger. (P9) suggested to "Add things to indicate what it does before doing it. Like a sensory cue," and (P37-VR) said "there could be like a voice, alerting people that it is coming". Researchers explored drone's movements to communicate emotions [79] or intents [42, 87, 344] and preferred acknowledgment distances [192].

3) Reduce threats' saliency: The propellers, camera, and sound are prominent threatening components of the drone. As threat assessment relies on the perception and interpretation of sensory inputs, decreasing their salience might help orient participants' focus on other components and reduce the resulting perceived threat. (P13) and (P21) suggested it would be better “not being able to see" the propellers, remove the lights (camera) or "reduce the sound" (P1). The reduced visibility of propellers has already been mentioned as a factor for decreased threat perception in favour of other components (sound) [391]. Similarly, participants in Yeh et al. [389]

social proxemic experiment reported not thinking about the propellers because they focused instead on the displayed face.

4) Increase drone's safety: It was also suggested to objectively decrease the threats. From a design perspective, (P12) "increase the size of the guard propellers" or (P14) "if the propellers were at the back I know that there's no chance of it interacting with my hair." But also its size "because bigger drone means bigger propellers and a more dangerous object closer to me" (P36-VR). While (P7) proposed soft material for the propellers, Nguyen et al. [266] recently presented safer deformable propellers. On a flying behaviour side, its position in space with regards to the participants' position, and flying speed has also been reported as critical. (P23) said "If it was higher (not in the eyes' line) it would not be a problem" which is congruent with previous HDP findings [58]. Some participants revealed being much more alert when it was close compared to when it was far. Indeed, as illustrated by (P2), "you never really know what happens if it's close to you." Finally, (P0) said that "more speed. It could be terrifying".

5) Limit sensory inputs: The annoyance resulting from the overwhelming sensory inputs (sound, air) following the drone's approach has been reported as a major concern by participants. It is congruent with previous findings [76]. The space people maintain with others also serves at maintaining an acceptable level of arousal stimulation [11, 227, 282], which is compromised by sensory overload. Reducing the sound level and produced air would probably greatly improve the drone's proximity acceptability. While the noise from rotors and downwash generated are not negotiable with the available state of technology of consumer drones, we argue that there is a need to push the boundaries to minimize the drawbacks of today's drones. VR can help investigate features that are unfeasible today, to guide the manufacturing of future drones.

Defensive Behaviours

In a scenario where the drone would have continued approaching participants until impact, they reported reactions that perfectly fit with the "3 Fs" of defensive behaviours: fight, freeze, or flight [44]. **Flight** - Some participants would have tried to avoid the drone with more or less intensity such as (P34-VR) "I would have left the chair definitely." or (P6) "I would have bent." **Fight** - Some others said they would have attacked, like (P33-VR) "I would hit it with my hands like I would do to a mosquito." or (P18) "My instinct was to hit it away." **Freeze** - Finally, some participants reported they would not have moved away, as (P36-VR) "I would have closed my eyes and step back a little bit." or (P9) "There's a strong chance I would be sitting here whispering is it going to stop, is it going to stop?". Their reactions are of different natures and intensities and might be representative of the interaction between the perceived threat level, the moment at which they would have intervened (the shorter, the more intense and instinctive the response) [45], and their personality [284]. It is no doubt that the experimental context has influenced these responses. When asked whether they would react similarly in a real situation, participants generally reported more intense and precocious defensive reactions suggesting larger defensive spaces. (P20) reported that “in the real life, I wouldn’t let the drone approach me that close". (P19) “would most probably punch it.” if it came as close as the intimate frontier. During the experiment, some participants believed the drone could not hurt them because they were in a controlled environment and they trusted the experimenter. But all these certainties fall out when leaving the experimental context. (P1) said "If it’s outside, it’s more like someone intends to attack me or something.”, (P19) “I don’t know who is behind that. I don’t like it", (P9) “It’s like what is happening and why is it happening?”. But also (P16) "with a known person, I think I would be fine.” It is congruent with previous research linking risk assessment with danger ambiguity [44]. It also highlights the impact of a controlled experimental environment on participants’ risk assessment (and therefore ecological validity) even without visible safety mechanisms.

Virtual Reality

The real group, having experienced a real drone, reflected on what affected their reactions and provided valuable feedback to make the VR experience of HDP more ecologicaly valid. Responses fit into five categories (visual, sound, haptic, distances, environment) and emphasize the importance of **1)** the sensory inputs dynamic’s accuracy, indicating the drone’s location relative to the participant and **2)** the replica of threatening components. For the visual category, (P20) said "It would have the propellers as that’s how I would distinguish the drone from something else.", for the sound (P14) said “If you can control the sound [relative to my] position, it’s a bit more real because I would be able to associate the distance with the sound” and (P19) "The noise as well, I mean these components that felt threatening.” For the distances, (P19) said it was important to replicate “how close it came to my face.” and (P18) "it needs to come to me at my eye line, I think.” Apart from the air induced by the drone’s propellers, our virtual environment matched these requirements as supported by participants’ feedback. When asked what made the environment feel not real, (P29-VR) said "No nothing at all. Everything was accurate." Some participants reported missing objects (e.g., their bag), poor resolution, and avatar mismatch (e.g., skin color).

4.5 Discussion

We found that a drone’s state and location can induce significant stress among participants, and that these factors also correlate with the drone’s perceived level of threat. We found no significant effect of the drone’s speed or the environment on participants’ stress, discomfort, and distance ratings. Semi-directed interviews allowed the identification of potentially threatening components during HDI and guidelines to mitigate their impact (see section 4.4.3). This section provides a discussion of these results.

4.5.1 Threatening Drones

Unnoticed Speed

While participants reported the drone's speed as an important factor for the threat assessment, it had no significant effect on stress, threat perception, or discomfort. Participants had not been informed that speed would vary and we asked them during the interview whether they noticed the velocity variation. Less than 50% of them noticed the drone going 4 times faster or slower between the conditions. We expect the way the experiment was designed (5 minutes of resting period between conditions) and presented (focused on the drone's stop distance) distracted participants from the drone's speed in favor of its proximity. Ultimately, most participants did not perceive the speed variation and interpreted both conditions as the same. According to the Situational Awareness model, filtered perception and interpretation of sensory inputs are the first steps in the process of understanding current and future states of a given situation [115]. This means an input that exists but is not processed should not impact the situational evaluation process. Nonetheless, it does not necessarily mean the input is not important. It emphasizes the subjective nature of threat perception and supports the proposed guideline "Reduce threat's saliency".

Proximity, Behaviour and Defensive Space

The drone's proximity was associated with greater stress and discomfort amongst participants. We explain these results considering the cognitive appraisal theory [133], risk assessment process [44, 45], defensive peripersonal space [96, 309], and protective function of proxemic [11, 103]. The drone's presence triggers a vigilance behaviour (increased watchfulness) associated with the detection of a potential threat [44, 133]. Hence participants reported shifting their attention from the environment towards the drone when it took off, but drifted away after some time. Then, we argue that there is a threshold distance (defensive space) below which participants' perceived ability to avoid the drones' threat becomes significantly compromised (ratio demand/available resources) [133] and that defensive behaviours occur to reduce the threat level. Such defensive reactions would increase in intensity with the magnitude of the perceived danger [309] and as the distance from the threat decreases (from escape, hiding, to defensive threat, to defensive attack [44]). Within this space (defensive space), attention is focused on the threat and the body gathers resources to face it (inducing stress). The measured perceived stress supports this explanation and participants reported being much more alert when the drone was close compared to far. (P16) said "here (close) it can attack me anytime and there (far) it wouldn't matter. It was too far." (P22) added that "The weaving was less disconcerting when it was further away" suggesting an interacting effect between proximity and drone's behaviour on the interpretation of sensory inputs and risk assessment. Intruding the defensive space in a non-natural way or when defensive reactions are not possible (e.g., experimental context, crowded environment, social norms) would induce discomfort in that it triggers a physiological need that cannot be fulfilled (i.e., reduce the threat level). Considering the approach, as the distance decreased perceived danger might have increased in parallel with the changing uncertainty that the drone would stop, and higher demand/ability ratio. Hence, even though the looming of visual stimuli instinctively triggers defense mechanisms, we believe this induced more stress than the other phases as the highest perceived situational danger occurred right before the drone stopped.

4.5.2 Validity of Virtual Reality

In readiness for the use of VR as a valid methodological tool for the HDI field, this study investigated the impact of VR on people's perception near drones. We found no significant differences between the real and virtual environments and similar results in both. As mentioned earlier (see section 4.4.3), these results might be explained by the sensory inputs dynamic's accuracy, indicating the drone's location with respect to participants' position and the replica of the threatening components. In other words, the elements involved in the evaluation of the situation with regards to participants' position. However, VR can impact critical factors such as the perception of distances [187, 253], motor abilities [128], or threat perception [101, 139]. We, therefore, expected each measure to be significantly different between the two environments. Regarding the perception of distances, we believe the transfer of depth markers (chairs, tables, experimenter) of the same size and position from the real world to VR helped participants develop an accurate distance estimation. For motor abilities, we used a wireless headset, hand-tracking, and participants' position was calibrated to be the same between the two environments. They were able to use their hands, freely get up from the chair and move without worrying to collide with anything (even though it never happened in the study). Then for the threat perception, we noted an impact of VR, as some participants reported not being afraid of the drone due to the virtual context. Yet similar comments have been reported by participants from the real-world setting, replacing "virtual" with "experimental" context. Threat perception might have been equally biased between both environments.This study shows that VR is extremely promising and can successfully replicate real-world results. Beyond the regular considerations of VR designs (maximize immersion), new recommandations for researchers willing to use VR for Human–Drone Proxemics include 1) identifying the relevant underlying mechanisms linked to the variables under investigation, 2) acknowledging the extent to which VR can alter these elements, and 3) limiting VR's impact through accurate replication of these elements. In our case, the relevant underlying processes are linked to threat perception and situational appraisal but it depends on the focus of the proxemic experiment.

4.6 Chapter Conclusion

This chapter delved into the impact of drone presence on individuals' perceived stress and discomfort, examining various drone behaviors and locations, and their relationship with perceived threat levels. While prior studies have suggested that drones can be seen as potential physical or privacy-related threats, the detrimental consequences of such perceptions, as well as the applicability of theories related to defensive mechanisms and stress management in human–drone interactions, had not been comprehensively explored until now.

Our work aimed to fill this gap by determining the applicability of threat perception theories in human–drone interactions. By doing so, it sought to provide a thorough explanation of people's behaviors around drones and predict their potential negative impacts when deployed in inhabited environments. This theoretical foundation also supports the development of mitigation approaches. The investigation also helps understand the significance of defensive proxemic behaviors around drones, whether the space people dynamically maintain from drones corresponds to a safety margin to keep perceived threats manageable and enable escape if necessary, as observed with other threats.

We collected participants' perceived stress while they experienced different human–drone interaction scenarios, including drones hovering at far and close distances, and approaching at two different speeds. By setting expectations based on relevant theories, we aimed to verify whether these theories could explain our observations, thereby validating their relevance in understanding human behaviors around drones and defensive proxemic behaviours.

In parallel, this chapter examined the validity of using Virtual Reality (VR) to study human–drone interactions, particularly regarding the perception of a virtual drone and people's responses. VR offers significant advantages for such studies, addressing limitations like restricted drone design options, safety concerns, and legal or technical complexities. However, our initial use of VR (see study #1 of chapter 3) revealed some concerns about its effectiveness in simulating threat perception and eliciting realistic defensive reactions to virtual drones. Despite achieving high levels of immersion, some participants in the VR setting exhibited behaviors that would be dangerous in real-world scenarios. These observations indicated that VR might alter participants' perception of danger, leading them to act differently than they would with an actual drone. This finding underscores VR's dual potential: it is valuable for safely observing risky behaviors that cannot be ethically or safely studied with real drones, but it also necessitates further investigation to ensure that threat perception in VR accurately reflects real-world reactions. We conducted the study in both a real-world environment and its virtual replica, designed to maximize immersion and elicit natural reactions from participants. We assessed direct measures and trend differences, as well as participants' feedback on their experiences with the drone in both settings. This approach allowed us to evaluate the potential of VR as a reliable tool for investigating human–drone interactions and understanding how VR findings translate to real-world scenarios.

This study confirms our concerns regarding the potential negative impact of integrating drones into close social spaces on people's well-being. Participants' reactions during passive interaction with a drone aligned with expected responses to perceived threats. Stress levels increased based on situational risk and were strongly correlated with the intensity of the perceived drone's threat level. Participant discomfort significantly varied within their personal space and was also correlated with the drone's threat level. In sensitive situations, such as policing scenarios where individuals may already feel anxious or threatened, or search and rescue operations where they may be distressed or vulnerable, it is crucial to ensure that drone interactions do not further escalate discomfort or distress. Incorporating insights and guidelines from our research can help tailor drone designs to prioritize user well-being and minimize potential negative effects on individuals' emotional states. We also advocate for significant shifts in drone designs, moving beyond the default four-propellers model to offer more alternatives. This study also contributes to developing VR as a proxy for HDI experiments, enabling researchers to explore possibilities beyond real-world constraints.

4.6.1 **Research Question 1.2 –** What is the role of the Defensive Proxemic Function in HDI?

The work presented in this chapter confirms our expectation that people perceive drones as threats and therefore engage in the cognitive and behavioral processes detailed below during a drone encounter. This provides a comprehensive understanding of the role of the defensive proxemic function in human-drone interactions.

The Role of The Defensive Proxemic Function

Defensive proxemics refers to the way people use physical space to protect themselves from perceived threats. This concept is part of a larger process where individuals evaluate their environment and employ defensive strategies to manage perceived risks effectively. Determining the most adaptive response often involves substantial cognitive activity on the part of the defensive individual [72].

- **Cognitive Appraisal** When encountering a new element in their environment, such as noticing a drone, individuals engage in a mental process known as cognitive appraisal to evaluate whether the situation poses a threat to their well-being [133]. This appraisal process involves two essential steps:
  - *Primary Appraisal:* This step focuses on assessing the level of demand, uncertainty, or danger associated with the situation. It involves evaluating how threatening or challenging the encounter with the drone might be.
  - *Secondary Appraisal:* This step involves determining whether one possesses

the necessary resources or abilities to manage the situation effectively. It assesses whether one can cope with the demands posed by the encounter [48].

This is a dynamic process that updates with each perceived change in the situation, such as a reduction in distance or a shift in behavior, which explains the changes in perceived stress based on situational risks during the study. The process is highly sensitive to individual differences, which accounts for the wide range of reactions observed in response to the same stimuli. Factors such as personality traits and past experiences significantly influence how a person assesses a given encounter and evaluates their ability to cope with it. For example, when faced with a spider, some individuals might quickly run away or attempt to step on it if it gets too close, whereas an entomologist might handle the spider calmly and confidently. Additionally, objective differences among individuals, such as varying motor skills or specialized knowledge, also affect their ability to deal with a situation. For instance, while an entomologist might have the knowledge to manage a spider safely, others might lack the same expertise and react differently.

- **Situational Awareness:** Linked to this process, situational awareness involves understanding the current and future states of one's environment by processing sensory inputs and interpreting them. It is important to note that, as with proxemics, this process relies on sensory integration. This is nicely illustrated in our work, where both speed conditions being perceived similarly yielded similar subjective reactions, indicating consistent situational assessment. Research on situational awareness is often conducted in task-performance contexts, where individuals must manage a situation while performing a task, modeling how they continuously monitor and anticipate changes in their surroundings to maintain safety and effectiveness. Yet, as with cognitive appraisal, this process is subject to various obstacles or "demons" [115] that can distort perception and interpretation of sensory inputs, ultimately leading to poor awareness and understanding of a situation.

Ultimately, these cognitive processes shape individuals' behavioral responses to the drone's presence.

- **Behavioral Response:** Research by Blanchard and colleagues on defensive mechanisms among rodents, and their applicability to humans, indicates that the dominant defensive response to discrete and clearly threatening stimuli depends on the individual's understanding of the situation, which stems from the cognitive processes mentioned above [44]. More specifically, this response varies based on factors such as perceived dangerousness, escapability, distance between the threat and the subject, ambiguity of the threat, and availability of concealment or protection [73].

> Generally, if there is a perceived escape route, flight is the predominant response; if escape is not possible, freezing occurs. We observed this behavior during pilot testing, which resulted in an accident when the drone drifted too close to the participants. Instead of moving away, they froze, leading to the propellers getting tangled in their hair. In the context of Human-Drone Interaction, the adaptive response individuals may adopt to maintain the threat at a manageable level is maintaining a safe distance from the drone, which can be considered a flight strategy. This helps keep the perceived threat at a manageable level, allowing the individual to evade the drone if necessary. As the distance between the threat and the subject decreases, defensive threats or attacks become more likely. When the threat is ambiguous or not clearly localized, risk assessment (RA) becomes the dominant response, involving actions to gather information and facilitate an adaptive decision.

Our work clearly supports these insights from human responses to threats, with our measures aligning well with expectations derived from cognitive appraisal theory and the situational awareness model. Participants reported projected behaviors consistent with those anticipated by behavioral defense literature. Understanding the role of these mechanisms in Human-Drone Interaction (HDI) is crucial, as it sheds light on how drones operating in inhabited spaces can disturb individuals, potentially leading to detrimental effects such as increased stress, diverted attention, and hazardous triggered behaviors. This underscores the importance of drones maintaining appropriate proxemics in social settings, as close proximity can cause significant stress and provoke defensive reactions, posing risks to both individuals and the drones. Ultimately, defensive proxemics is one of several strategies that help to dynamically regulate perceived threats, balancing stress levels and coping resources to maintain an acceptable threshold of safety.

These insights from the literature provide a solid theoretical foundation for explaining human behaviors around autonomous drones. While the influence of factors driving people's behaviors around drones might shift over the years with safer and more social drones, it remains relevant to consider defensive proxemics as a major determinant of people's proxemics around current drones, which are often perceived as non-social and threatening.

4.6.2 Contribution to Research Question 2 – How best to use VR to study human-drone proxemics?

Guidelines for an Optimal Use of Virtual Reality in HDI

Our work aimed to address concerns regarding the validity of using virtual reality (VR) for studying human responses to drones, specifically in terms of perceived stress, discomfort, and threat. Given the uncertainty about whether virtual drones elicit reactions similar to real drones, we conducted a comparative study between real and virtual settings, exposing participants to various drone behaviors and situational risks. The results revealed no significant differences between the two environments, suggesting that VR can be a valid tool for this research context, though not universally applicable.

We developed a methodological protocol based on VR literature to address potential discrepancies between virtual and real environments, aiming to enhance ecological validity and facilitate external evaluation of virtual human-drone interaction (HDI) experiments. This multi-step approach includes:

1. **Identifying Key Mechanisms** associated with the variables under study: We identified cognitive appraisal (how participants evaluate the threat) and situational awareness (how they understand and interpret their environment) as key processes influencing responses to drones.

2. **Assessing VR's Impact:** We reflected on how VR technology might influence these processes. Key aspects included sensory perception (how well the VR replicates the appearance and behavior of drones) and immersion (how realistic the VR environment feels).

3. **Minimizing VR's Influence:** To minimize VR's impact on outcomes, we designed a virtual environment to closely mimic the sensory dynamics of the real setting. This included accurate representation of the drone's location, threatening components (e.g., moving propellers), and addressing known VR issues such as distance compression and motor abilities. We used a VR setup that replicated the real environment's dimensions and visual cues, ensured similar motor abilities by tracking hand movements and avoiding cables, and maximized immersion through high-fidelity drone design, sound, and haptic feedback.

This protocol, ensures that VR studies are conducted and reported with transparency, aiding researchers in achieving valid results and allowing readers to evaluate the generalizability of the findings. Such transparency supports future researchers in assessing the relevance of past findings as VR technology evolves.

Applying this framework to virtual reality (VR) studies in human-drone interaction (HDI) provides two key benefits. First, for researchers exploring similar mechanisms, this framework creates a foundational base of knowledge that can be reused to ensure consistency and reliability across studies. It helps standardize the approach to understanding VR's impact and offers established mitigation techniques. Second, for investigations into novel mechanisms, the framework generates new insights into how VR affects participant responses and how these effects can be mitigated. This contributes to a growing body of knowledge about VR's role in HDI and informs the development of new strategies to enhance VR research. For example, in our studies, we applied this framework to examine different proxemic functions associated with drones. This approach not only provided a consistent method for evaluating VR's impact but also uncovered new insights into how VR influences participant behavior and how these effects can be managed. The knowledge we gathered through this process is compiled and summarized in chapter 8, demonstrating how the framework supports both the reuse of established techniques and the discovery of novel insights for future research.

4.6.3 Contribution to Research Question 1.5 – How do multiple proxemic functions interact in HDI?

Other Carrier Mechanisms: *Arousal Regulation, Communication, Goal-oriented*

While this study primarily focuses on the proxemic protective function [103, 309], we acknowledge that other carrier mechanisms may have been involved during the experiment and in HDI more broadly. In fact, we believe HDP behaviours to be the result of a weighted mean of the active spaces surrounding the individual in the given situation, aligning Miller's theory [258] of approach and avoidance forces.

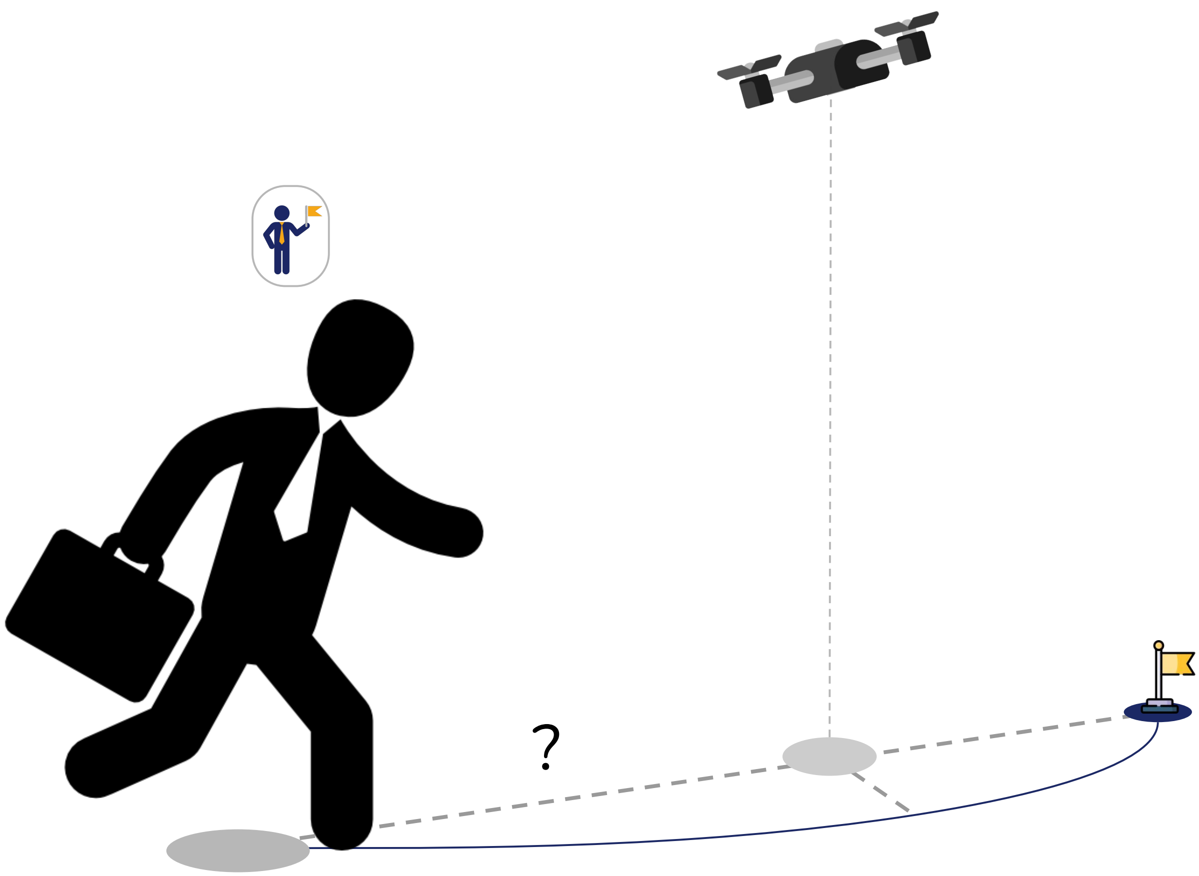
- We observed indicators of the arousal regulation function [11, 282], particularly related to sensory overload caused by the drone's loudness. Despite its critical role in design and frequent mention in participant feedback, the impact of sound in drones remains underexplored due to challenges in controlling it in real-world settings. Chapter 6 addresses this by presenting a study on how varying sound levels affect subjective arousal, preferred distances, and task performance under different working memory loads. This exploration illuminates the intricate role of arousal regulation in shaping human–drone proxemics.
- Additionally, feedback from some participants indicates that the communicative function [11, 163] played a role, albeit marginally. Two participants seemed to per-

ceive the drone as a social entity. For example, one participant (P20) noted, "I've never encountered a thinking drone, so it's like meeting a new person," while another (P13) mentioned, "My brain still kind of thinks it's a living creature, so I still kind of try to look into its eyes (camera)." These observations imply that incorporating anthropomorphic features, such as faces [172, 389] and eyes [272], can enhance user engagement but also introduce new design challenges, as discussed in chapter 3. Furthermore, P20's preference for distance, expressed as "that's how I talk to people," suggests a dimension of socially driven proxemics, in line with its social perception of the drone.

- Finally, it seems that some participants selected their preferred distance based on the drone's task (face detection), reflecting the goal-oriented proxemic function [96]. This suggests that their choices were motivated by considerations of task efficiency rather than comfort, safety, or social norms. Additionally, our investigation into situational awareness has yielded new perspectives on previous research. It reveals that contextual factors related to the tasks individuals are engaged in can significantly influence how situations are perceived, including the processing and interpretation of sensory information, which can vary with the task. This also points to a possible shift in how individuals assess risky situations, balancing potential benefits against perceived risks rather than focusing solely on personal comfort. For instance, in Study #1 of chapter 3, some participants, despite feeling uncomfortable around drones, were focused on the task, suggesting that the discomfort (avoidance force) was outweighed by the need for task efficiency (approach force). These new insights, including the impact of goal-oriented behavior on human-drone proxemics, are explored further in chapter 5.

Chapter 5

The Goal-Oriented Proxemic Function



5.1 Chapter Introduction

Goal-oriented proxemics refers to how individuals use physical space to achieve specific, task-related objectives within a given context. These actions involve practical adjustments, such as navigating efficiently through an environment or maintaining an optimal distance from objects or people to accomplish a goal, whether it's completing a task, reaching a destination, or avoiding obstacles. For example, when someone is walking through a crowded room to exit quickly, they weave between people and objects, navigating their environment with a clear purpose. However, goal-oriented proxemics often requires a delicate balancing act between practical task achievement and competing proxemic mechanisms, such as adhering to social norms or avoiding potential dangers.

5.1.1 Motivation

Why Assessing the Goal-oriented Proxemic Function? While Chapters 3 and 4 have clarified the roles of communicative and defensive functions in the use of space, another function remains underexplored: the goal-oriented proxemic function. Despite indications of its significant influence on how individuals navigate around or interact with autonomous drones, this aspect has yet to receive sufficient attention. The tasks individuals undertake, along with their psychological impacts and the behaviors they trigger, may profoundly shape how people approach encounters with drones and manage the surrounding space. This suggests the existence of a distinct, goal-oriented mechanism that meaningfully interacts with other proxemic functions. Tied to contextual factors, the role of goal-oriented proxemics in human-drone interaction remains largely uncharted, leaving its potential influence hidden beneath an opaque veil. In this chapter, we aim to lift that veil and delve into the underlying factors that drive goal-oriented behaviors in human-drone proxemics.

As individuals carry out their daily tasks, they must navigate around these autonomous aerial devices. However, this dynamic—where individuals and drones operate independently in shared spaces—has largely gone unexplored within the Human-Drone Interaction (HDI) field, which has traditionally focused on direct interactions. Understanding this interaction flow may represent a significant aspect of future drone applications, especially in environments such as construction sites or warehouses, where autonomous drones and human operators coexist. Therefore, comprehending the specific considerations arising from this context is a crucial initial step toward implementing effective proxemic strategies for autonomous drones. This understanding is essential for facilitating their seamless, efficient, and safe integration into populated spaces.

5.1.2 Overview of the Study #4: *"Safety at Stake: How Individuals Task Prioritization Influences Human-Drone Proxemics"*

Motivation Similar to the interpersonal distances observed among humans, individuals may naturally deviate from their planned paths to fulfill their tasks when encountering a drone. These deviations can affect their efficiency in reaching their intended destinations and their overall performance in accomplishing their objectives. A key question arises: to what extent does the importance individuals assign to their tasks influence the degree of deviation they are willing to accept? This question holds particular significance in work environments where performance is important. However, its relevance extends beyond the workplace, as urgency often arises in daily scenarios, such as swiftly maneuvering through a crowd to catch a departing subway train. Moreover, addressing this question holds importance in research, shedding light on how proxemic observations in Human–Drone Interaction (HDI) studies may be affected by individuals modifying their behaviors to improve performance under observation, a phenomenon known as the Hawthorne effect. This lays the foundation for our initial research inquiry:

- **RQ1:** How does individuals' motivation to complete tasks affect their navigation behavior around drones?

In situations where drones are tasked with handling potentially hazardous materials or pose safety risks themselves, maintaining appropriate safety distances is crucial to prevent accidents and foster a low-risk environment, thus mitigating the stress induced by the presence of drones [59]. Understanding how individuals juggle the necessity of accomplishing their tasks with the requirement to uphold safe distances is paramount. This consideration brings us to the second research question:

- **RQ2:** To what extent do goal-oriented behaviors impact the defensive proxemic function in Human–Drone Interaction (HDI)?

Our hypothesis is that participants' task prioritization will significantly influence their proxemic behaviors around drones. Specifically, when the importance of the task increases (i.e., high task priority), individuals will be more likely to stick to the shortest path (less deviation) and take risks to complete the task efficiently (lower maintained distance from the drone in dangerous condition), but they will still maintain a minimum safety distance when interacting with drones. In contrast, low task priority will result in more cautious behaviors, with participants prioritizing safety over task completion.

Study Design & Methodology To address these questions, we conducted a user study within a Virtual Reality (VR) environment, involving 26 participants. Immersed in the virtual environment (whose design is detailed in subsection 5.3.1), participants and a drone engaged in tasks requiring the movement of objects between different locations, operating under two *Task Priority* conditions: either *Low–Relaxed Scenario* or *High–Competitive Scenario* (see section 5.3 for details). By controlling the objects to be relocated and their designated destinations, we orchestrated encounters between humans and drones (see Figure 5.3), thereby observing natural proxemic behaviors in a setting where both entities autonomously pursued their respective objectives (RQ1). To assess the influence of goal-oriented behaviors on the defensive proxemic function (RQ2), we introduced varying levels of risk, labelled as *Drone's Danger*, associated with the drone's cargo. Specifically, the drone transported either ordinary, harmless boxes (*Low–Normal Cube*) or hazardous red boxes (*High–Explosive Cube*), which triggered an explosion upon contact with the participant. Leveraging this unique setting and utilizing the capabilities of the virtual environment (see subsection 5.3.1), we expanded conventional proxemic metrics, such as minimum distance, to include novel metrics like participants' walking speed and deviation from their shortest path (outlined in subsection 5.3.2). This novel methodological approach allowed for a more comprehensive understanding of individuals' proxemic behaviors.

Results Our findings reveal a significant shift in behavior based on task priority levels, illuminating its impact on the defensive proxemic function (see subsection 5.4.3). In particular, we observed a significant interaction effect between the two variables, with participants allowing more deviation from the shortest path due to the explosive payload only in the low task-priority condition. Participants walked significantly faster in the High Task Priority condition, indicating both an increased motivation for efficiency but also potentially a strategic use of speed to evade the drone while adhering to the shortest path and maintaining a consistent safety distance. Indeed, participants maintained a significantly greater distance from the drone in the dangerous condition, irrespective of task priority. At the same time, other findings suggest a direct impact of high task priority on the weight of the defensive proxemic function, including the negative correlation between self-reported drive for performance and maintained distances, as well as participants' feedback indicating a greater willingness to take risks in competitive scenarios. Ultimately, the results present several non-exclusive interpretations, potentially reflecting diverse performance/safety trade-offs among participants, which are further discussed in section 5.5. Importantly, our work shows that acknowledging perceived task priority, especially when high, holds paramount importance in HDI. It significantly impacts how users navigate drones, potentially prompting them to employ risky maneuvers in pursuit of optimal performance.

5.1.3 Chapter Structure

This chapter follows a structure similar to the previous one, adhering to the format of the original paper it is based on. It begins with a related work section that offers a focused synthesis of studies relevant to the specific investigation at hand, providing readers with the necessary background to grasp the research gap, our approach, and the findings. The methodology section then outlines the approach used to address this gap, highlighting the development of a novel environment with enhanced validity compared to earlier studies. In this environment, both participants and the drone evolve independently, allowing for the observation of natural proxemic behaviors within the intended interaction context outlined in the introduction. The chapter concludes with a summary that encapsulates the objectives and main findings of our research. Following this summary, we provide detailed responses to RQ 1.3, "What is the Role of the Goal-Oriented Proxemic Function in HDI?" based on the findings. Additionally, we offer partial answers to RQ 2, "How can VR be effectively used to study human-drone proxemics?" and RQ 1.5, "How do multiple proxemic functions interact in HDI?"

5.2 Related Work

This section sets the stage for our study by summarizing key findings and highlighting gaps in these areas. This section offers an overview of the research landscape on the specific topics addressed in this Chapter, highlighting the novelty and value of our methodological approach, with a novel interaction context investigated.

A comprehensive literature review of general proxemics, including human–drone proxemics and virtual reality, is presented in chapter 2. In contrast, this section narrows its scope to focus specifically on studies and related work that are directly relevant to the current investigation and the particular proxemic function under examination.

5.2.1 Human–Drone Proxemics

The majority of studies on human-drone proxemics employ the stop-approach procedure as their methodology for assessing individuals' proxemic preferences. In this procedure, the drone approaches a stationary participant under various conditions (e.g., different flying altitudes [107], drone designs [4, 389], speeds [382]), and participants indicate at which distance, termed the stop-distance, they would prefer the drone to halt. While this approach allows researchers to empirically identify factors influencing the distance individuals maintain from drones in a controlled environment, and contributes to advancing our understanding of human-drone proxemics when appropriate theories are considered [59,227], it remains somewhat distant from real-world experiences. Importantly, the process of distancing from one another is largely intuitive, relying on the perception and interpretation of sensory inputs [163]. Conscious awareness of these inputs can alter responses, potentially leading participants to provide responses that do not accurately reflect how individuals would behave around drones in more realistic settings. Additionally, due to the artificial experimental setup, the stop-approach procedure fails to capture the specific considerations that may arise in more authentic interaction contexts. Yet contextual factors, including environmental or task-related ones are specifically what has been understudies in the broad Human–Robot Proxemics field so far, as outlined by a recent meta analysis of human–robot proxemics [227]. An important gap that our research aims to address.

Task-Related Factor

In chapter 3, we identified early indications that task-related contextual factors could significantly influence individuals' proxemic behaviors [57, 58]. In Study #1, participants had to navigate around a hovering drone to reach various locations. Some participants mentioned that concentrating on the task at hand diverted their attention away from the drone, which may have reduced their perception of threat and consequently led to shorter distances maintained from the drone. This observation aligns with the situational awareness model, whose relevance was highlighted in chapter 4.

While previous studies introduced scenarios where participants naturally interacted with a stationary drone, the research presented in this chapter goes further by exploring interactions where both the participants and the drone are active and move independently within a shared space. Additionally, we previously highlighted limitations in the metrics used to measure proxemic behaviors, particularly the focus on minimum maintained distance. We emphasized the need to explore new proxemic measures that capture a broader spectrum of behaviors—an aspect that our current research also addresses.

In related work involving ground robots, Leichtmann et al. (2022) examined the impact of working memory load on people's comfort distances. Although they did not find a direct effect, they observed that tasks with higher working memory loads led to increased emotional arousal and decreased perceived control, which in turn resulted in larger comfort distances [226].

Defensive Behaviours

In the existing literature, numerous studies have highlighted the potential for drones to be perceived as threats [82, 391]. In the previous chapter, we presented our research that underscored the crucial role of the defensive proxemic function in Human-Drone Interaction (HDI), showing that people tend to maintain greater distances when they perceive a higher threat from a drone [59]. What sets our work apart in the study presented in this chapter, is its focus on how individuals respond to contextual dangers, such as those that may arise on construction sites where autonomous drones carry hazardous objects [15, 16]. Our primary emphasis, however, is on exploring the interaction between the defensive proxemic function and goal-oriented behaviors in HDI.

Interplay Between Proxemic Driving Mechanisms

The expanding body of knowledge on Human-Drone Proxemics suggests the involvement of multiple driving mechanisms, as highlighted by insights from our previous studies presented in

Chapters 3 and 4. We have introduced the concept that individuals' proxemic behaviors around drones are influenced by a weighted combination of proxemic spaces, often conceptualized as "bubbles" [96, 163], linked to these various mechanisms [59]. The weight given to each factor fluctuates based on the individual's priorities in a particular situation. While our earlier work has focused on empirically demonstrating the roles of specific driving mechanisms, such as Defensive [59] and Communicative [57], the interaction between these mechanisms remains largely unexplored. This chapter addresses this gap by delving into how different driving mechanisms interact to shape proxemic behaviors around drones. Specifically, we explore how varying levels of priority assigned to Goal-Oriented Behaviors, driven by task requirements, interact with the weight of defensive proxemic behaviors. This investigation occurs within the context of two entities autonomously navigating a shared space. By using virtual reality, we create an ecologically valid, safe, and controlled environment that allows for precise and enhanced behavioral measurements.

5.3 Methodology

This research investigates how individuals' drive to accomplish a task affects their proxemic behaviors while navigating around an autonomous drone in a shared space. Our specific focus lies in evaluating how varying levels of task-oriented motivation may affect individuals' defensive proxemic responses to the drone.

Observing Natural Proxemic Behaviours As highlighted in Hall's early work on social proxemics [163], the process of distancing from one another is not a deliberate and conscious decision, but rather an instinctive reaction to various sensory inputs. In this study, we adopted an approach utilized in prior proxemic research [31, 58, 263] to observe natural participants' proxemic behaviors. Essentially, participants are instructed to perform a task that necessitates navigation around the object of interest, unaware that their movements are being monitored by the experimenter (interactional method). The key distinction from the referenced works and from Human-Drone proxemic studies employing such approach is that both participants and the drone were in motion in our study. This presents a unique case of proxemic interaction, still unexplored in to this date. Immersed within a virtual environment, both participants and the drone engaged in tasks involving the movement of objects between different locations. By controlling the objects to be moved and their destinations, we could induce human-drone encounters (see Figure 5.3) and observe natural proxemic behaviours. Within this setting where both entities operate autonomously in a shared space, our first objective was to investigate the impact of individuals' task-driven motivation on the dynamics of their navigation around the drone. Given this specific context and leveraging the virtual setting (whose implementation is detailed in subsection 5.3.1), we enhanced the traditional proxemic metric (i.e., minimum distance) with additional novel metrics such as participants' walking speed and deviation from their shortest path (see subsection 5.3.2). This approach aims to offer a more comprehensive characterization of individuals' proxemic behaviors.

Manipulation of the Goal-Oriented Motivation Participants navigated around the drone multiple times to move objects in two scenarios, each involving different levels of task priority: either *low* (Relaxed Scenario) or *high* (Competitive Scenario). In the *low priority condition*, participants were instructed to move the objects as if they were tidying their rooms. There was no timer, and it was emphasized that they prioritize their safety and comfort in an atmosphere intended to be relaxed. In contrast, in the *high task priority condition*, participants were informed that they were competing with others to earn a reward based on how quickly they completed their task. A timer was displayed in the room, turning red after 10 seconds. In both scenarios, participants were reminded not to collide with the drone, particularly when it was carrying the red boxes, as it would trigger an explosion upon contact. The explosion was demonstrated to them beforehand in a video. Since task-priority is subjective, we conducted manipulation checks (detailed in subsection 5.3.2) after each scenario to verify how they influenced participants' subjective drive to perform well. These manipulation checks are particularly crucial because we were concerned that the competitive mindset induced by the high task priority condition might persist into the relaxed scenario, potentially compromising the manipulation of task priority and subsequent behaviors for participants who began with the competitive scenario. While one potential solution could have been to consistently conduct the relaxed scenario first, this approach would have made it unclear whether observed behavioral differences were attributable to repeated exposure to the drone rather than variation in task priority.

Effect on the Defensive Proxemic Function Should behavioural differences be observed and assuming that different driving mechanisms come at play when exhibiting proxemic behaviours around drones (e.g., Social, Arousal Regulation, Defensive), the approach described above does not enable us to discern which specific proxemic function is affected by the goal-oriented motivation, thereby offering only a limited understanding of the observed phenomena. Another question we address, with potentially significant implications for the deployment of drones in performance-focused environments, is whether goal-oriented behaviors significantly impact defensive proxemics in Human-Drone Interaction (HDI). The defensive proxemic function has been empirically demonstrated and explained in our prior Human-Drone Proxemic study [59] (see chapter 4). Drones present potential physical and privacy-related threats, eliciting defensive responses from individuals, such as maintaining greater distances. These behaviors serve to keep the perceived threat at a manageable level and contribute to safeguarding individuals' integrity. Understanding how task-oriented behaviors might impact the role of the defensive proxemic function in individuals' behavior is crucial to predict and prevent unsafe situations in

Human-Drone interactions, where compromised safety considerations can endanger individuals. To discern the impact of goal-oriented behaviors on the defensive proxemic function, the drone transported either ordinary harmless boxes or hazardous red boxes that triggered an explosion upon contact with the participant. While it can be expected that individuals maintain a greater safety distance from the drone when it carries hazardous objects, this approach allows us to evaluate how this defensive response differs between the low and high task priority conditions. Ultimately, this enables us to gain a deeper understanding of the influence of goal-oriented behaviors on people's defensive proxemic responses in HDI.

5.3.1 Setup and Apparatus

Design of Virtual Environment

This study employs the experimental setup described in section 2.3.2. Participants wore a Meta Quest 2 and navigated the room alongside a moving virtual drone to perform their tasks in the virtual space (see Figure 5.1). Furthermore, participants utilized handheld controllers to interact with 2D virtual screens and directly respond to questions within the VR environment. This approach aimed to minimize breaks in presence compared to exiting and re-entering the virtual environment [294]. Drawing from previous proxemic research utilizing VR technology [31,57], we used the VR headset's positional data within the Immersive Virtual Environment (IVE) to capture participants' paths during navigation around the drone (see Figure 5.3) and accurately assess proxemic metrics across the various experimental conditions (see subsection 5.3.2).

Ecological Validity In this section, we adhered to the framework we introduced in chapter 4 (see subsection 4.6.2), to enhance the ecological validity and enable external evaluation of virtual Human-Drone Interaction (HDI) experiments [59]. This framework entails three key steps: **1)** identifying the behavioral mechanisms associated with the variables under study, **2)** recognizing how these mechanisms might be influenced by virtual reality (VR), and **3)** outlining the strategies devised to minimize VR's impact on the observed outcomes.

In this study, we specifically focus on two mechanisms: goal-oriented and defensive behaviors. Goal-oriented behaviors in VR may be affected if the capabilities to perform the task differ from those in the real world. However, as previously mentioned, the motor capabilities in terms of navigation closely resemble those in the real world. Additionally, interacting with objects in VR closely mimics real-world actions; participants must reach for the cube with one controller, and it remains attached to their hand as long as they hold the grip button, simulating the sensation of holding an object. To acclimate participants to this interaction method and ensure their confidence in navigating the virtual environment, the study includes a practice session. This approach aims to significantly minimize the impact of VR on participants' ability to perform the task naturally.

Figure 5.1: The virtual experimental room depicted in Unity 3D. On the left side of the image, there is a virtual screen providing a description of the current scenario to the participant. Below this screen, a button "Start" is visible, which the participant can click to initiate the task. Numerous cubes were distributed among the chairs and tables in a predefined and consistent manner for both scenarios. Participants are tasked with identifying the highlighted cube among these scattered objects (see Figure 5.2).

Regarding defensive behaviors, our previous research indicated that VR can induce similar threat perception as a real drone [59]. Importantly, we identified that the design of the drone (detailed in section 5.3.1), including the accuracy of sensory inputs dynamics, both auditory and visual cues, coupled with the replication of threatening components like propeller sounds and rotation, contributes to inducing a similar threat perception of the drone. Another challenge we encountered was inducing varying levels of danger associated with the drone and its payload to elicit diverse defensive behaviors. We were concerned that real-world dangerous objects, such as a knife, wouldn't be perceived as sufficiently threatening in VR to induce defensive reactions when compared to a drone carrying a harmless object. This concern motivated the use of explosive boxes (see Figure 5.2), which would trigger a significant and loud explosion within the virtual environment, causing the boxes to fly around and have undesired real consequences on the environment. While we did not expect participants to react to these explosive boxes in VR as they would to actual explosives in the real world, our aim was to have the drone carry an object that would be perceived as potentially harmful even in VR, triggering defensive reactions from participants when present. This way, observed behaviors could be comparable to what might be observed if a drone carried dangerous objects in a real-world collocated situation. One potential limitation to consider is the absence of virtual avatars for participants, which might have impacted their ability to visualize potential collisions with the drone and their overall body awareness and positioning within the virtual environment. However, since the controllers were visible, we believe that individuals' proprioception ability and intuitive navigation were sufficient for them to behave naturally in the virtual environment.

Figure 5.2: Explanation of the different box appearances and their significance is as follows: Normal cubes, which do not possess any specific meaning, are susceptible to being carried by the drone. Highlighted cubes, distinguished by their alternating appearance between normal and yellow, are intended to be easily discernible by participants amidst other boxes. Participants are tasked with identifying and moving these cubes to another location. When the drone transports a box that turns red, it signifies an explosive payload. Colliding with this box triggers a significant explosion, intended to evoke a heightened sense of danger associated with the drone compared to when it carries normal boxes. The explosion produces a powerful auditory blast, a visual representation of explosive effects, and a physical force that propels the surrounding cubes away from the detonation point.

Design of Drone

In this study, we employed a 3D model of the DJI Tello drone (98 x 92.5 x 41 mm) to simulate the drone. To heighten the sense of realism, we utilized high-quality recordings of an actual flying drone to generate the sound effects within the virtual environment as in our previous studies. The pitch of the drone's sound was adjusted to closely resemble that of a DJI Tello in flight. Furthermore, the spatialization of sound was implemented, ensuring that the sound balance in participants' headphones dynamically shifted in direction and intensity based on their relative position (including distance and orientation) to the drone. Additionally, the 3D model was animated to replicate the rotating propellers and subtle variations in movement while hovering. These techniques have proven effective in evoking a sense of threat from the drone in our previous works, with participants reporting that the virtual drone felt real [59] (see chapter 4).

The drone's flight behavior was controlled by C# scripts, which utilized coroutines to handle actions like hovering, navigating to specific locations, and interacting with objects such as picking up and dropping boxes. To ensure seamless transitions between points, we employed both linear interpolation (Lerp) and spherical interpolation (Slerp) functions in Unity. These interpolation techniques were further refined with animation curves to mimic real-world drone movements, resulting in a more realistic flight within the virtual environment. The drone maintained a flight path at participants' eye level, with the altitude adjusted individually based on the height of each participant's headset. This adjustment ensured consistency and aimed to mitigate any potential impact of height variations on proxemic preferences. Prior studies have suggested that interacting with a drone at eye level enhances the naturalness of the interaction for participants [76, 109]. The drone's speed was set to reach 1.5 m/s and included acceleration/deceleration phases, a rate comparable to the average human walking pace documented in the literature [49]. While this speed exceeds the preferred approach speed observed in prior studies at 0.5 m/s [382], it's important to consider the task-oriented context of our experiment. In our scenario, both the participant's and the drone's behaviors are directed towards accomplishing specific tasks rather than approaching one another. Furthermore, the progression of both participants and the drone was synchronized to ensure uniform passing situations for all participants (as described in the subsequent subsection). If the drone was too slow during task execution, it could significantly impede participants' ability to complete their own tasks.

Design of the Task

Upon entering the simulation, participants face a virtual screen that provides an overview of the current scenario characteristics (Practice, Relaxed, or Competitive). Once participants have reviewed the scenario details and are ready to proceed, they initiate the task by clicking on the start button on the screen using the controller. Similar to the familiar actions of pointing and clicking with a mouse on a computer, participants utilized the controller's ray casting for pointing and the trigger button to activate the start button. Simultaneously, upon activation of the start button, the drone initiated its task by taking off and moving, with its objective mirroring that of the participant but involving different cubes. Within the virtual environment, numerous cubes are distributed among the chairs and tables in a predefined and consistent manner for both scenarios (see Figure 5.1). Participants are required to identify the highlighted cube, distinguished by its alternating colors shifting between normal and yellow over time (see Figure 5.2). They then approach the cube and grab it by pressing the grip button of the right or left controller when in close proximity. Upon grabbing the cube, the drop location becomes visible, prompting participants to navigate to the designated area and deposit the object within the highlighted zone. Subsequently, another cube is highlighted, and participants repeat the process of reaching, grabbing, and dropping the object. After moving several cubes, the drone cease flying, and the virtual screen reappears, signaling the end of the scenario. Participants are then prompted to answer a series of questions before progressing to the next scenario by clicking on the "Continue" button.

Progress Synchronization Due to the anticipated variability in task completion times among participants, independent progression of both the drone and participants would have led to inconsistent crossing scenarios, complicating the measurement and comparison of proxemic behaviors. To ensure uniform passing situations for each participant across experimental conditions while maintaining a natural setting, we synchronized the progress of both the drone and participants. Specifically, the drone could not retrieve its cube until participants had obtained theirs, and the dropping zone for participants did not appear until the drone had retrieved its cube. This approach allowed us to determine the locations of participants and the drone at specific moments, as well as when they would commence movement toward their next target location. By controlling the target locations this enabled us to induce consistent passing situations (see Figure 5.3) between participants and across scenarios throughout the entire experiment.

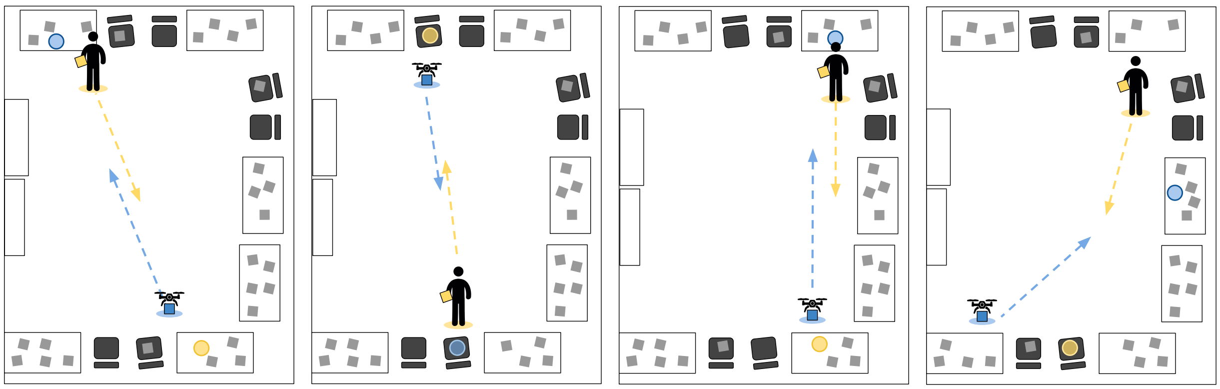


Figure 5.3: Schematic representation of the four passing situations intentionally induced in both task-priority conditions by controlling the positions of the boxes to be grabbed by participants and the drone, along with the locations and activation of the dropping zones. Participants' direction, their box, and associated dropping zone are depicted in yellow, while those for the drone are shown in blue. Throughout the study, participants were unaware of which cube the drone was required to grab or where it would drop it. Additionally, the drone transported an explosive box twice but non-consecutively among these four situations, with the order randomized for each participant but remaining consistent between task-priority conditions. For each of these situations, participants' positions are tracked over time to extract their walking speed, deviation from the shortest path, and minimum distance maintained with the drone, as detailed in subsection 5.3.2.

Data Collection

Throughout the study, a combination of quantitative and qualitative data was collected to assess and comprehend the impact of the experimental conditions. Implemented in Unity, the majority of recorded data were obtained from various virtual objects known as GameObjects within the virtual environment. To access information about these virtual objects, we utilized C# scripts, which allowed us to write the data into dedicated .txt files.

Tracking Data Throughout the study, we continuously recorded the positions (including 3D coordinates and orientation) of participants and the drone at a frequency of 10Hz using tracking data from the headset and the Drone GameObject. Each recorded sample included the timestamp, current task-priority and drone danger level, as well as information regarding participants' and the drone's target boxes or dropping zones. These data were stored in dedicated proxemic .txt files for each participant, providing a comprehensive record of the study's progress.

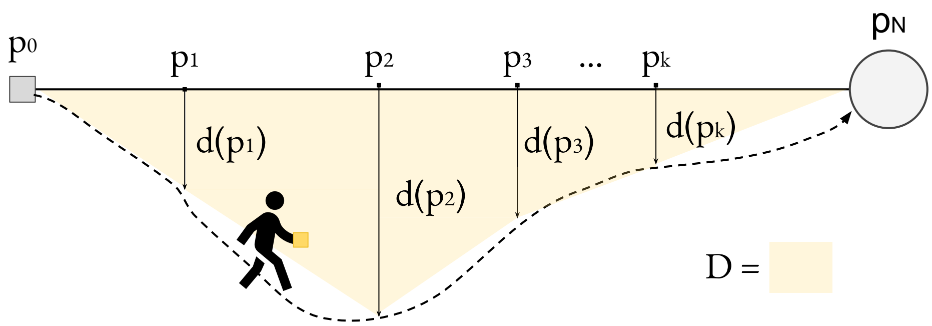
The positions of the various cubes and dropping zones were predetermined and known in advance. This allowed us to compute various proxemic measures relevant to each set of conditions (see subsection 5.3.2), which served as dependent variables in the subsequent statistical analysis.

Questionnaires When participants successfully moved a sufficient number of boxes, a virtual screen appeared at their starting position. This screen presented questions along with sliders for participants to provide their responses. Using the right VR controller, which projected a laser pointer, participants could interact with the virtual screen by pressing the trigger button of the controller and adjusting the sliders to select their preferred values. These values were recorded in dedicated question .txt files for each participant and for each scenario condition.

5.3.2 Study Design

The study employs a 2x2 within-subject design with two independent variables: "Task Priority" (2 levels: Low - Relaxed Scenario, High - Competitive Scenario) and "Drone's Danger" (2 levels: Low - Normal Box, High - Explosive Box). The order of the experimental conditions is randomized using a Latin square design. Proxemic dependent variables, derived from participants' positions tracked at 10Hz, include walking speed, deviation from the shortest path, and minimum maintained distance from the drone. These measures are relevant to understanding how goal-oriented behaviors influence proxemics when navigating around autonomous drones.

Walking Speed (m/s)	Walking speed was measured as the distance covered between two consecutive positions, with both average and peak speeds calculated for each human–drone encounter. Average speed reflects participants' general pace, while peak speed captures sudden movements like dodges or accelerations.
Total Deviation from the Shortest Path (m^2)	The shortest path is defined as the straight line from the participant's initial position (upon grabbing the cube) to its drop location. Deviation from this path reflects the impact of the drone on goal-oriented navigation and participants' motivation. Deviation $d(p_k)$ is calculated as the distance between a participant's recorded position and its orthogonal projection on the shortest path. Instead of using the average deviation, which is sensitive to walking speed, we calculate the area between the participant's route and the shortest path, denoted as D, as illustrated in Figure 5.4.
Minimum Maintained Distance (m)	For each set of conditions, we employed the minimum distance maintained by participants from the drone (measured in meters) as a proxemic index. This metric offers valuable insight into how closely individuals are willing to approach the drone and is widely employed in proxemic studies [31,58], enabling comparisons with previous research findings.



$$D = \sum_{k=0}^{N-1} \frac{d(p_k) + d(p_{k+1})}{2} \Delta p_k \tag{5.1}$$

Figure 5.4: Illustration of the trapezoidal rule used to approximate the total area between the shortest path for task completion and the participant's actual route. For each sampled position k, $d(p_k)$ represents the distance between the participant's position and its orthogonal projection p_k onto the shortest path. This process generates a series of trapezoids, and by summing their areas, we approximate the total deviation from the shortest path, denoted D.

Participants' Perception To gain further insights into participants' experiences and behavior during the task, we collected self-reported measures related to stress and subjective driving factors, as outlined below:

Self-Reported Stress (*0-100*)	After each scenario, participants rated the level of stress they experienced while performing the task. They could select a value ranging from 0 to 100, categorized as follows: Very Light (0-20), Mild (20-40), Moderate (40-60), High (60-80), and Extreme (80-100). While self-reported measures may not always accurately reflect actual physiological stress levels [118], they provide valuable insights into participants' subjective perception of the situation and are commonly utilized in research [59, 323].
Subjective Driving Factors (*1-5*)	After each scenario, participants rated on a 5-point Likert scale the extent to which performance, comfort, or safety influenced their behavior. They answered: **1)** "To what degree did the goal of finishing quickly drive your behavior?" **2)** "To what extent was your behavior driven by comfort?" **3)** "How much did concerns for safety influence your behavior?" The first question also served as a manipulation check for the competitive and relaxed scenarios.

Post-experiment After the experiment, we conducted 15-20 minute semi-structured interviews to gain deeper insights into participants' behavior, their responses to the collocated and dangerous conditions, and their perspectives on autonomous drones in various contexts. The interview guide, containing questions for each theme, can be found in the appendix (see Appendix C). To analyze the qualitative data, we employed an affinity diagram approach [245], which enabled systematic organization of participants' feedback into coherent themes, as seen in previous works [57, 59]. Initially, we immersed ourselves in the data during transcription, followed by an inductive coding process to identify significant concepts. These were then recorded as digital sticky notes and displayed on a virtual whiteboard for further analysis. Axial coding was applied to identify relationships between these concepts and establish categories, providing a comprehensive understanding of the factors driving participant behaviors. Additionally, participants completed the Igroup Presence Questionnaire (IPQ) [315] and the Fast Motion Sickness Scale (FMS) [204] to assess their immersion and motion sickness levels within the virtual environment.

Pre-Experiment Questionnaires Before the experiment, participants completed a demographic questionnaire capturing variables such as gender, age, drone experience, and cultural background, as these factors could influence proxemic behaviors [109]. For instance, familiarity with drones, and VR experience may affect comfort levels and perceived motor abilities, potentially altering proxemic distances. Gender and cultural background can also influence proxemic behavior, with studies indicating cultural differences in proximity preferences with drones [109]. Additionally, participants completed an adapted version of the Negative Attitudes towards Robots Scale (NARS) [267, 268] to assess their attitudes toward drones, as previous research has shown that NARS scores predict reactions to drones [42].

5.3.3 Protocol

Participants were invited to take part in an experiment investigating human behavior in collaboration with a drone. The invitation included essential documents such as the Participant Information Sheet, Consent Form, and a scheduling link via Calendly. Upon arriving at the laboratory on the scheduled date and time, participants were warmly greeted and provided with written informed consent. The subsequent steps participants underwent are depicted and explained in Figure 5.5. **(1)** Participants completed demographic information and responded to an adapted version of the NARS on the experimenter's computer. **(2)** Following the initial assessment, participants received a detailed participant protocol document outlining study procedures and interaction methods. The experimenter ensured proper alignment between the virtual and real positions of the headset in the room. **(3)** Participants donned the VR headset and immersed themselves in a replica of the experimental room. They engaged in a practice session to familiarize themselves with the experimental task. This involved activities such as grabbing and dropping cubes at various locations in the room and interacting with the virtual screen. **(4)** Participants proceeded with the experimental task in the order of scenarios assigned to them based on the Latin square design. They were instructed to locate and grab the highlighted cube, then deposit it within the designated zone. This process repeated for subsequent cubes while avoiding the drone, which occasionally carried explosive boxes. **(5)** Upon completing the experimental task, participants answered a series of questions designed to assess their experience. This included measures such as the Immersive Presence Questionnaire (IPQ) and the Feeling

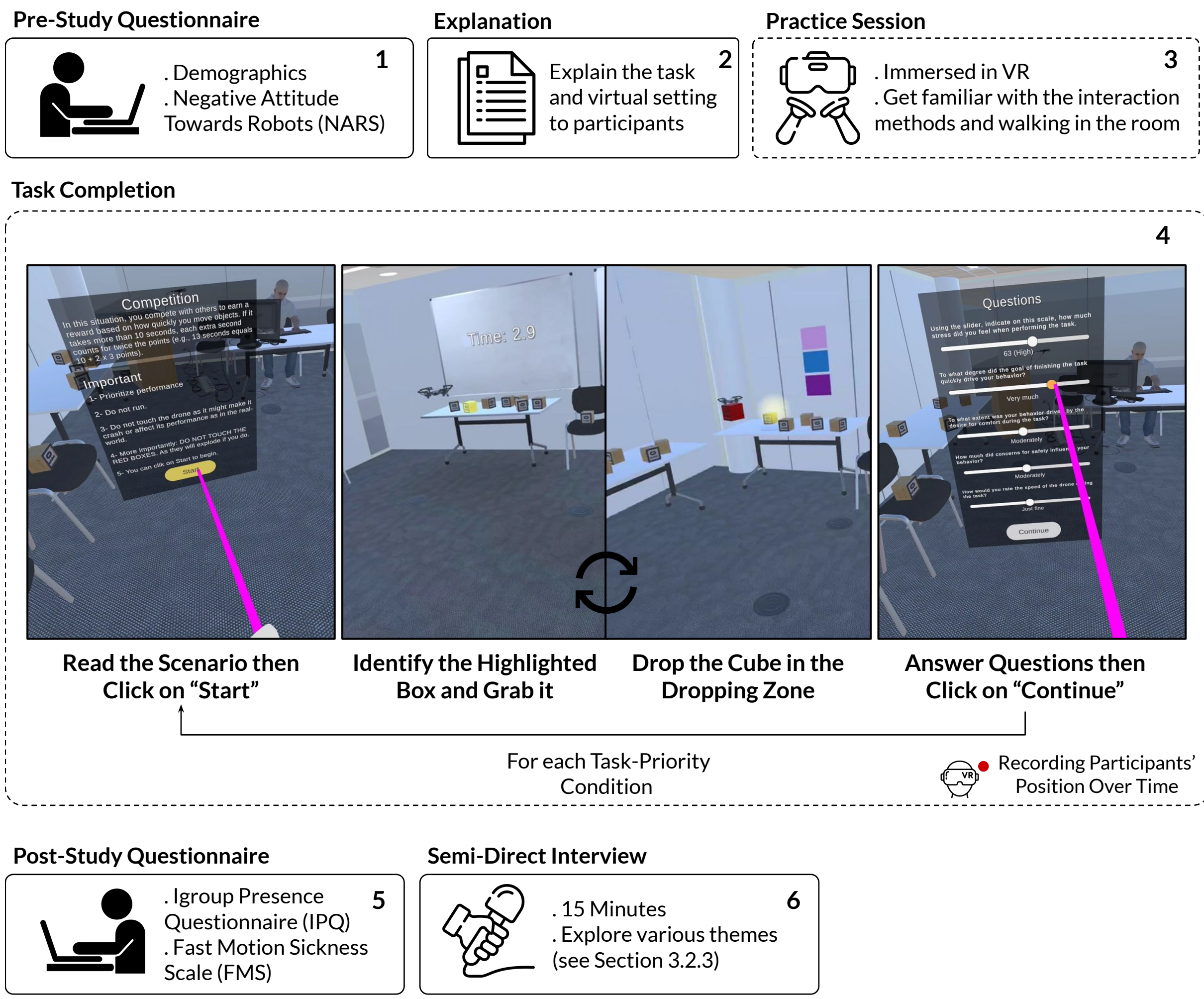


Figure 5.5: Diagram of participants' Protocol. The process begins after participants have been welcomed and have signed the consent form. Dotted lines indicate steps occurring in the virtual environment, while solid lines represent actions in the real world. **(1)** Participants provided demographic information and completed the NARS on the experimenter's computer after signing the consent form. **(2)** Participants received task instructions and specifics of the virtual environment. The experimenter clarified instructions, answered questions, and showed a video demonstration of an explosive box. **(3)** Participants were immersed in the virtual environment and underwent a practice session without the drone. They performed the experimental task in a simplified environment, allowing them to grab and drop boxes, navigate, and interact with the virtual screen. **(4)** Participants proceeded with the experimental task by initiating it after reviewing scenario details and clicking "Start". Upon activation, the drone commenced its task, mirroring that of the participants. Participants were tasked with locating and grabbing the highlighted cube, then depositing it within the designated zone. This process repeated for subsequent cubes while avoiding the drone, which occasionally carried explosive boxes. After moving multiple cubes, the drone ceased flying, and the virtual screen reappeared, marking the scenario's end. Participants then answered questions before advancing to the next scenario by clicking "Continue" or removing the headset after completing both scenarios. **(5)** Participants proceeded to answer the IPQ and FMS on the experimenter's computer. **(6)** The study concluded with a short semi-directed interview exploring key themes detailed in subsection 5.3.2.

of Presence (FMS) scale on the experimenter's computer. **(6)** The study concluded with a short semi-directed interview exploring key themes detailed in the study design. Participants had the opportunity to provide additional insights and feedback on their experience during the experiment. The total experiment took approximately 45 minutes. Participants were debriefed and thanked in the end.

5.3.4 Participants

We recruited 26 participants, comprising 7 males and 19 females. Our sample size aligns with the standards established by the HCI field for within-subject designs [70] and is comparable to or larger than the sample sizes used in previous studies concerning human-drone proxemics, some of which utilized similar or smaller sample sizes [107, 389]. Our pool of participant is relatively young, with age ranging from 18 to 33 and a mean age of 23.26 suggesting good and similar motor abilities. Participants were asked to indicate the region they identified with as their main cultural background, with the option to select multiple regions. The distribution of responses is as follows: Asia Pacific (13), Europe (9), Middle East (4), Africa (1), Latin America (1). In terms of prior experience with drones, 3 participants reported never having seen a drone (No experience), 18 had seen a drone (Little Experience), and 5 had used drones (Quite a bit of Experience). Alongside demographic information, participants' prior negative perceptions of drones were assessed using an adapted version of the Negative Attitude Towards Robots Scale (see subsection 5.3.2). A summary of demographic data is available in Table 5.1. In the results section, we report the statistical tests conducted to examine the impact of these pre-assessed potential confounding factors on proxemic behaviors, although no significant effect was found. Recruitment was conducted through the university's mailing list and word of mouth, with all participants providing informed consent before participating in the study. The research received ethical approval from the University of Glasgow Ethics Committee (reference number: 300220100).

5.4 Results

In the results section, we begin by examining the potential influence of various pre-study factors, including previous experience with drones or virtual reality (VR), pet ownership, gender, and prior negative perceptions of drones, on our proxemic metrics. Our analysis found no significant effects attributable to these factors (see subsection 5.4.1).

Following this, we explore how the scenarios used to manipulate our independent variable *Task Priority* influenced participants' perceptions of the task and their underlying behavioural motivations, such as performance considerations, safety concerns, and comfort (see subsection 5.4.2). We also investigated the potential impact of the order in which participants experienced the scenarios.

Table 5.1: Demographics Summary

Number of Participants		26
Gender	Male	7
	Female	19
Age	M	23.26
	SD	4.31
	Range	18-33
Cultural Background (Top 5)	India	8
	United Kingdom	7
	Thailand	2
	United Arab Emirates	2
	China	2
Drones' Experience	None	3
	A Little	18
	Quite a Bit	5
	A Lot	0
VR Experience	None	3
	A Little	14
	Quite a Bit	6
	A Lot	3
Pet Owner	Yes	16
	No	10
NARS [M,SD]	NARS	[-0.14,0.5]
Subscales	Interaction	[-0.44,0.75]
	Social	[0.17,0.56]
	Emotion	[-0.14,0.79]

Next, we explored the impact of our independent variables, *Task Priority* and *Drone's Danger*, on participants' proxemic behaviors, considering metrics detailed in subsection 5.3.2, including average and peak walking speed, total deviation from the shortest path, and minimum maintained distance. As anticipated, we observed a main effect of Drone Danger on the minimum maintained distance, with participants maintaining a significantly greater distance from the drone when it carried explosive boxes. Interestingly, a significant interaction emerged between *Task Priority* and *Drone's Danger* regarding total deviation from the shortest path. Specifically, the presence of the drone carrying an explosive cube induced significantly greater total deviation compared to when it carried normal cubes, but this effect was observed only in the relaxed scenario. This suggests the influence of goal-oriented motivation on defensive behaviors. Moreover, *Task Priority* significantly impacted average and peak walking speed, which were notably higher in the high task priority condition (Competitive) (see subsection 5.4.3). Furthermore, we examined correlations between participants' subjective ratings of the factors driving their behavior and the proxemic metrics. Generally, a drive to perform the task was negatively correlated with the minimum maintained distance and total deviation from the shortest path, while average and peak walking speed showed positive correlations with perceived stress. Considering the potential impact of scenario order, we conducted the same tests for each order group.

Finally, we present the analysis of semi-directed interviews, organized into themes outlined in the interview guide. These themes include participants' approaches to the collocated situation, the influence of independent variables on their responses, their perceptions of future independent co-working situations, and their experiences in the virtual setting.

To assist readers in navigating through the results, we incorporated summary boxes which emphasize the findings related the proxemic behaviours.

5.4.1 Confounding Variables

Prior to proceeding with the primary analysis, we assessed potential confounding variables that were measured before the study. The means of the proxemic metrics for each level of the categorical potential confounder are presented in Table 5.2. In summary, the proxemic metrics were not significantly affected by the individual characteristics measured before the study, except for participants' average walking speed. Surprisingly, pet owners walked significantly faster than non-pet owners, and the NARS subscale measuring negative attitude towards the social influence of drones is positively correlated with walking speed. We currently lack a logical explanation for these specific outcomes, although the mean difference between both groups is not particularly impactful given the study context, with an 8 cm/s speed difference. Given the unequal sample sizes between our groups, we opted for the Welch t-test instead of the standard Student's t-test to compare differences. The Student's t-test can be significantly biased and result in invalid statistical inferences when sample sizes differ across independent groups [119]. Our choice is also consistent with recent recommendations in psychology, which suggest using the Welch t-test as the default approach rather than the Student's t-test [97].

Genders

Welch's t-tests revealed that among the 26 participants, comprising 7 males and 19 females, there were no significant differences between genders in any of the measured proxemic metrics.

Minimum Distance	$t(22.11) = 0.47$, $p = 0.47$, $g = 0.27$, $M_{Male} = 1.22m$, $M_{Female} = 1.15m$
Total Deviation	$t(23.89) = -0.02$, $p = 0.99$, $g = -0.0063$, $M_{Male} = 3.56m^2$, $M_{No} = 3.57m^2$
Average Speed	$t(8.74) = -0.16$, $p = 0.88$, $g = -0.07$, $M_{Male} = 0.96m/s$, $M_{Female} = 0.97m/s$
Peak Speed	$t(8.79) = 0.35$, $p = 0.73$, $g = 0.15$, $M_{Male} = 1.51m/s$, $M_{Female} = 1.48m/s$

Pet Ownership

According to Welch's t-tests, there were no statistically significant differences between pet owners (N=16) and non-pet owners (N=10) for each proxemic metric except for average walking speed.

Minimum Distance	$t(22.26) = -0.46$, $p = 0.65$, $g = -0.17$, $M_{Yes} = 1.15m$, $M_{No} = 1.20m$
Total Deviation	$t(22.85) = -0.07$, $p = 0.94$, $g = -0.03$, $M_{Yes} = 3.55m^2$, $M_{No} = 3.58m^2$
Average Speed	$t(22.61) = 3.03$, ***p=0.0063* (*)**, $g = 1.15$, $M_{Yes} = 1.00m/s$, $M_{No} = 0.92m/s$
Peak Speed	$t(19.85) = 1.7$, $p = 0.11$, $g = 0.65$, $M_{Yes} = 1.52m/s$, $M_{No} = 1.43m/s$

Participants who reported owning a pet appeared to walk faster compared to those who did not own a pet. However, it's important to note that the groups were unbalanced, with a small sample size, which may have influenced the observed result. Given these limitations, the reliability and generalizability of this finding are uncertain.

Experience with Drones

Participants' familiarity and prior exposure to drones might influence their comfort levels in the drone's presence, as they may be accustomed to its characteristics such as sound and flying behavior. This familiarity could potentially impact their proxemic behavior during the study. However, Welch's one-way ANOVAs conducted among the 26 participants, categorized based on their reported level of experience with drones as None (3), A Little (18), Quite a Bit (5), or A Lot (0), revealed no statistically significant impact of participants' level of experience with drones on any of the proxemic metrics measured. The means for each level of this variable are presented in Table 5.2.

Minimum Distance	$F_{Welsh}(2, 5.24) = 1.64$, $p = 0.28$, $\widehat{\omega^2} = 0.14$
Total Deviation	$F_{Welsh}(2, 4.68) = 1.11$, $p = 0.40$, $\widehat{\omega^2} = 0.03$
Average Speed	$F_{Welsh}(2, 4.69) = 1.61$, $p = 0.29$, $\widehat{\omega^2} = 0.14$
Peak Speed	$F_{Welsh}(2, 4.61) = 0.45$, $p = 0.67$, $\widehat{\omega^2} = 0.00$

Experience with Virtual Reality

Participants' familiarity with VR could potentially influence their comfort and proficiency in navigating in the virtual room, thereby affecting their proxemic behavior in the study. However, Welch's one-way ANOVAs conducted among the 26 participants, categorized based on their reported level of experience with VR as None (3), A Little (14), Quite a Bit (6), or A Lot (3), revealed no statistically significant impact of participants' VR experience on any of the measured proxemic metrics. The absence of significant differences may be attributed to the specific experimental setup (as detailed in subsection 5.3.1), combined with the practice session. This session likely helped mitigate any prior familiarity discrepancies among participants.

Minimum Distance	$F_{Welsh}(3, 5.27) = 1.24$, $p = 0.38$, $\widehat{\omega^2} = 0.07$
Total Deviation	$F_{Welsh}(3, 6.02) = 1.23$, $p = 0.38$, $\widehat{\omega^2} = 0.06$
Average Speed	$F_{Welsh}(3, 6.11) = 1.75$, $p = 0.26$, $\widehat{\omega^2} = 0.18$
Peak Speed	$F_{Welsh}(3, 6.79) = 0.90$, $p = 0.49$, $\widehat{\omega^2} = 0.00$

Table 5.2: Average measures for each proxemic metric, categorized by Gender, Pet Ownership and Experience Levels with Drones and VR. This symbol ** indicate a significant effect of the variable on the proxemic metric. Welch's t-tests and One-Way Anovas revealed no significant effects of these variables on the proxemic metrics except for Pet Ownership on average walking speed.

	Total Deviation (m^2)	**Minimum Distance** (m)	**Average Speed** (m/s)	**Peak Speed** (m/s)
Gender	===========	=========	=========	=========
Male (N=7)	3.56	1.22	0.96	1.51
Female (N=19)	3.57	1.15	0.97	1.48
Pet Ownership	===========	=========	===**===	=========
Yes (N=16)	3.55	1.15	1.00	1.52
No (N=10)	3.58	1.20	0.92	1.43
Drones' Experience	===========	=========	=========	=========
None (N=3)	4.26	1.36	0.90	1.42
A Little (N=18)	3.43	1.14	0.97	1.49
Quite a Bit (N=5)	3.64	1.17	1.00	1.52
VR Experience	===========	=========	=========	=========
None (N=3)	3.40	1.10	0.93	1.51
A Little (N=14)	3.76	1.22	0.98	1.52
Quite a Bit (N=6)	3.01	1.05	0.99	1.44
A Lot (N=3)	3.93	1.27	0.91	1.39

Negative Attitude towards Drones

As depicted in Table 5.1, participants' average NARS scores are relatively neutral, hovering close to zero with small standard deviations. A Pearson correlation analysis was conducted to explore the connection between the adapted Negative Attitude Towards Robots Scale (NARS) scores and each proxemic metric. No significant correlations were observed, except for the subscale measuring negative attitude towards the social influence of drones, which showed a correlation with average walking speed ($r = 0.35$, $p = 0.017$).

5.4.2 Manipulation Checks

After each scenario, participants were asked to provide feedback regarding their subjective perception of what motivated their behavior during the task, as well as their self-rated stress. This assessment helps verify that the Task Priority condition has been effectively manipulated between low and high levels across the scenarios. They specifically provided ratings on a 5-point Likert Scale for the following questions: **1)** "*To what degree did the goal of finishing the task quickly drive your behavior?*" and **2)** "*How much did concerns for safety influence your behavior?*". To explore the main effect and interaction of the scenarios and the order in which participants experienced them on their responses, we utilized the ARTool package in R, which employs Aligned Ranks Transformation (ART) on the data, followed by a non-parametric factorial ANOVA [379]. Additionally, post-hoc pairwise comparisons with Holm adjustment using the extended ART-C procedure were conducted. [112]. The results of the statistical tests described below confirm the successful manipulation of the task-priority variable, indicating heightened priority in the competitive setting compared to the relaxed one. However, these results also shed light on the influential role of the scenario presentation order. Specifically, it appears that when the competitive setting is experienced first, its effect persists over the relaxed scenario, potentially influencing behavior consistently across both scenarios.

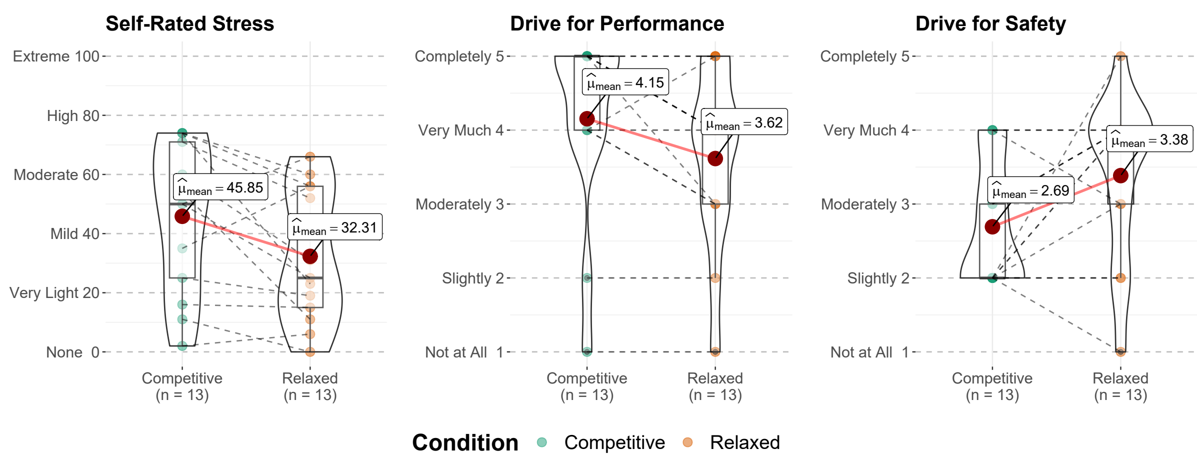


Figure 5.6: Boxplot and violin plots illustrating the responses of participants who commenced with the relaxed scenario (n=13) to the following questions answered after each scenario: (Left) "How much stress did you feel when performing the task?" (Middle) "To what extent did the goal of finishing the task quickly drive your behavior?" and (Right) "How much did concerns for safety influence your behavior?" An intriguing observation is the pronounced contrast between participants' drive for performance and safety in the competitive setting compared to the relaxed one. In the competitive setting, participants rated their behavior as Very Much to Completely driven towards performance ($M_{Performance} = 4.15$), whereas it was rated as Slightly to Moderately towards Safety ($M_{Safety} = 2.69$). In contrast, both performance and safety were considered similarly influential drivers of behavior in the relaxed setting, with ratings of moderately to very much for both ($M_{Performance} = 3.62$, $M_{Safety} = 3.38$).

Performance Overall, participants rated performance motivation as an important factor driving their behavior during the task, with responses ranging between Moderately and Very Much for both Competitive ($M_{Competitive} = 3.88$) and Relaxed ($M_{Relaxed} = 3.62$) scenarios. Our statistical test indicate a significant main effect of the scenarios ($F(1,24) = 5.03$, p=0.034) and a significant interaction effect between the impact of the scenario and the order in which they were performed ($F(1,24) = 5.03$, p=0.034). Regarding the main effect, Post-hoc comparisons revealed a significant increase in drive for performance from the Relaxed to the Competitive scenario ($p = 0.034$). For the interaction effect, post-hoc comparisons revealed a significant increase in drive for performance from the Relaxed to the Competitive scenario when performed in this order ($p = 0.048$), with responses ranging between Very Much to Completely ($M_{Competitive} = 4.15$) compared to Moderately to Very Much ($M_{Relaxed} = 3.62$). In contrast, there was no significant decrease in drive for performance from the Competitive to the Relaxed scenario when performed in this order ($M_{Competitive} = 3.62$, $M_{Relaxed} = 3.62$). These outcomes might suggest a lasting effect of the competitive scenario over the relaxed one, which warrants consideration for later analysis regarding the order in which scenarios are performed. However, the presence of a main effect validates the manipulation of the Task Priority variable through the scenarios in our study.

Safety Regarding safety considerations, participants rated it as being slightly to moderately influential regarding their behaviors in both scenarios ($M_{Competitive} = 2.62$, $M_{Relaxed} = 2.88$). Our tests revealed again a significant interaction effect between the impact of the scenario and the order in which they were performed ($F(1,24) = 5.06$, p=0.034). Post-hoc comparisons did not reveal a significant difference from the Relaxed to the Competitive scenario when performed in this order ($p = 0.08$), despite responses ranging between Slightly to Moderately ($M_{Competitive} = 2.69$) compared to Moderately to Very Much ($M_{Relaxed} = 3.38$) (see Figure 5.6).

Self-Rated Stress Participants' stress levels while performing the task ranged between Very Light (20) to Mild (40) in both conditions but were higher in the competitive scenario ($M_{Competitive} = 39.12$) compared to the relaxed one ($M_{Relaxed} = 30.46$). Our statistical test reveals a significant main effect of the scenarios, ($F(1,24) = 8.002$, p=0.009), with the competitive setting inducing significantly more stress compared to the relaxed one (p=0.009). Given the heightened drive to perform the task and reduced consideration for safety as indicated by the statistical tests above and illustrated in Figure 5.6, the increased stress in the competitive setting compared to the relaxed one may result from participants allocating more resources to perform the task or placing themselves in more hazardous situations. This observation aligns with the validation of using the scenario to induce varying levels of task-priority.

5.4.3 Proxemic Analysis

A two-way analysis of variance (ANOVA) was conducted to explore the impact of two independent variables: Task Priority (*Low - Relaxed Scenario, High - Competitive Scenario*) and Drone's Danger (*Low - Normal Box, High - Explosive Box*) on the participants average and peak walking speed, total deviation from the shortest path and minimum distance measured during the task. We assessed data for normality (Shapiro-Wilk test, p > 0.05) and verified homogeneity of variances (Levene's test, p > 0.05). Additionally, we addressed the sphericity assumption using Mauchly's test and applied the Greenhouse-Geisser sphericity correction for factors violating this assumption. All p-values were adjusted using the Bonferroni multiple testing correction method.

We extended the analysis by investigating potential correlations between participants' subjective ratings of behavioral drivers and stress and their observed proxemic behaviors. Additionally, the observed effect of scenario order on these measures prompted us to examine these correlations separately for each order group.

Total Deviation

The analysis revealed a significant main effect of Drone's Danger ($F(1,25) = 15.426, p = 0.0006, ges = 0.079$) and an interaction between effects of the Task Priority and Drone's Danger conditions ($F(1,25) = 4.762, p = 0.039, ges = 0.017$). The measures for each set of conditions are illustrated in Figure 5.7.

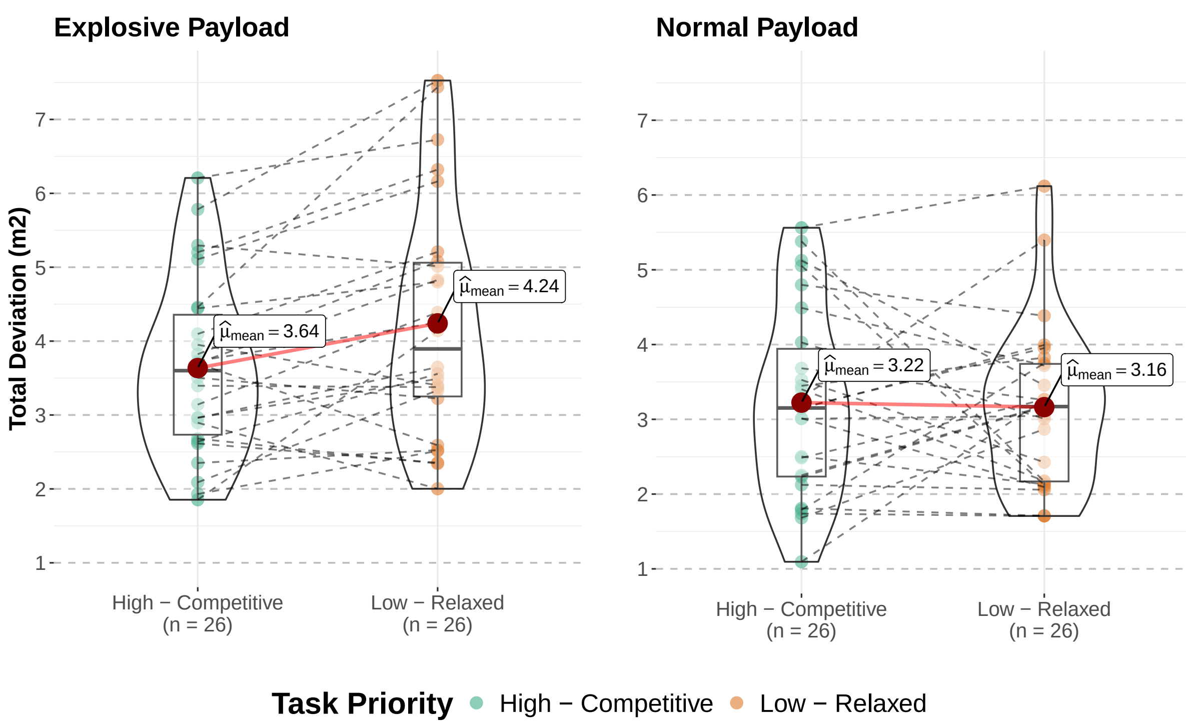


Figure 5.7: Boxplot and violin plots representing participants Total Deviation from the shortest path for each *Task Priority* and *Drone's Danger* conditions.

- Concerning the main effect, subsequent pairwise comparisons indicated that participants deviated significantly more from the shortest path ($p = 1.02e^{-4}$) when the drone carried an explosive box ($M_{Explosive} = 3.94m^2$) compared to a normal one ($M_{Normal} = 3.19m^2$).

- Regarding the interaction, we performed simple main effects analysis of each independent variable at each level of the other variable. Results showed a significant effect of Drone's Danger when participants performed the relaxed scenario ($F(1,25) = 25.8, p = 0.614e^{-4}, ges = 0.14$), with post-hoc comparisons again revealing a greater deviation from the shortest path in the High Drone's Danger condition ($M_{Explosive} = 4.24m^2$) compared to the normal one ($M_{Normal} = 3.16m^2$) ($p = 3.07e^{-5}$). However, there was no significant difference between normal and explosive payload when participants were in the High Task Priority condition ($p = 0.282$).

- Additionally, the simple main effect analysis showed a significant effect of Task Priority when the drone carried dangerous payload ($F(1,25) = 10.6, p = 0.006, ges = 0.046$) with participants deviating significantly less from the shortest path in the competitive scenario ($M_{Competitive} = 3.64m^2$) compared to the relaxed one ($M_{Relaxed} = 4.24m^2$) ($p = 0.003$). However, there was no significant difference between the competitive and relaxed scenario when the drone carried normal cubes ($p = 1$).

Correlations We observed a significant moderate negative correlation between the total deviation from the shortest path and participants' self-reported drive for performance ($r = -0.32$, $p = 0.05$). This correlation was more pronounced among participants who completed the relaxed scenario before the competitive one ($r = -0.51$, $p = 0.0019$), while it was not significant for the other group ($p = 0.77$). No other correlations were observed for the total deviation metric.

Finding 1 *Task Priority impacts the effect of Drone's Danger on participants' route*

- As anticipated, participants exhibited significantly greater deviation from the shortest path when the drone carried a dangerous payload, underscoring the defensive proxemic function's influence on individuals' behaviors around drones.

- Nevertheless, participants approached the explosive cubes differently depending on the level of Task Priority. Specifically, in the high Task-Priority condition, participants adhered more closely to the shortest path when the drone carried a dangerous payload compared to the low Task-Priority condition (see Figure 5.7), suggesting that their behavior was indeed more focused on efficiently completing the task.

- This is supported by the correlation analysis, showing that as participants adhered more closely to the shortest path, they also reported a stronger drive toward task completion.

- Furthermore, Task Priority influenced how participants responded to varying levels of drone danger. Specifically, during the relaxed scenario, participants deviated significantly more from the shortest path when the drone carried a dangerous payload compared to normal ones. However, this difference was not observed in the high Task-Priority condition. This aligns with our hypothesis that higher task-priority would diminish the impact of the defensive proxemic function on participants' proxemic behaviors.

Minimum Distance

The analysis revealed a significant main effect of Drone's Danger ($F(1,25) = 6.493, p = 0.05, ges = 0.037$), with participants getting significantly less closer from the drone ($p = 5.05e^{-3}$) when it carried explosive boxes ($M_{Explosive} = 1.23m$), compared to normal ones ($M_{Normal} = 1.11m$). Additionally, there is a trend of lower maintained distances and smaller differences between danger levels in the competitive condition (see Figure 5.8), although statistical significance was not observed.

Correlations We observed a significant moderate negative correlation between the minimum maintained distance from the drone and participants' self-reported drive for performance ($r = -0.34$, $p = 0.034$). This correlation was more pronounced among participants who completed the relaxed scenario before the competitive one ($r = -0.45$, $p = 0.039$), while it was not significant for the other group ($p = 0.72$). No other correlations were observed for the minimum maintained distance.

Finding 2 *Participants maintain a greater distance from the drone when it carries dangerous objects, but maintain shorter distances as their drive to perform the task increases.*

- As anticipated, participants got significantly less closer to the drone when it carried explosive boxes further highlighting the active role of the defensive proxemic function.
- Interestingly, despite the trends observed in Figure 5.8 indicating a potential influence of the Task Priority, no significant effect was found.
- However, we found that as participants perceived their behavior as more task-oriented, they also tended to maintain shorter distances from the drone. This suggests that goal-oriented behavior plays a significant role in human-drone proxemics.

Walking Speed

The analysis revealed a significant main effect of Task Priority on participants' average walking speed ($F(1,25) = 9.20, p = 0.018, ges = 0.159$) and peak walking speed ($F(1,25) = 25.619, p =$

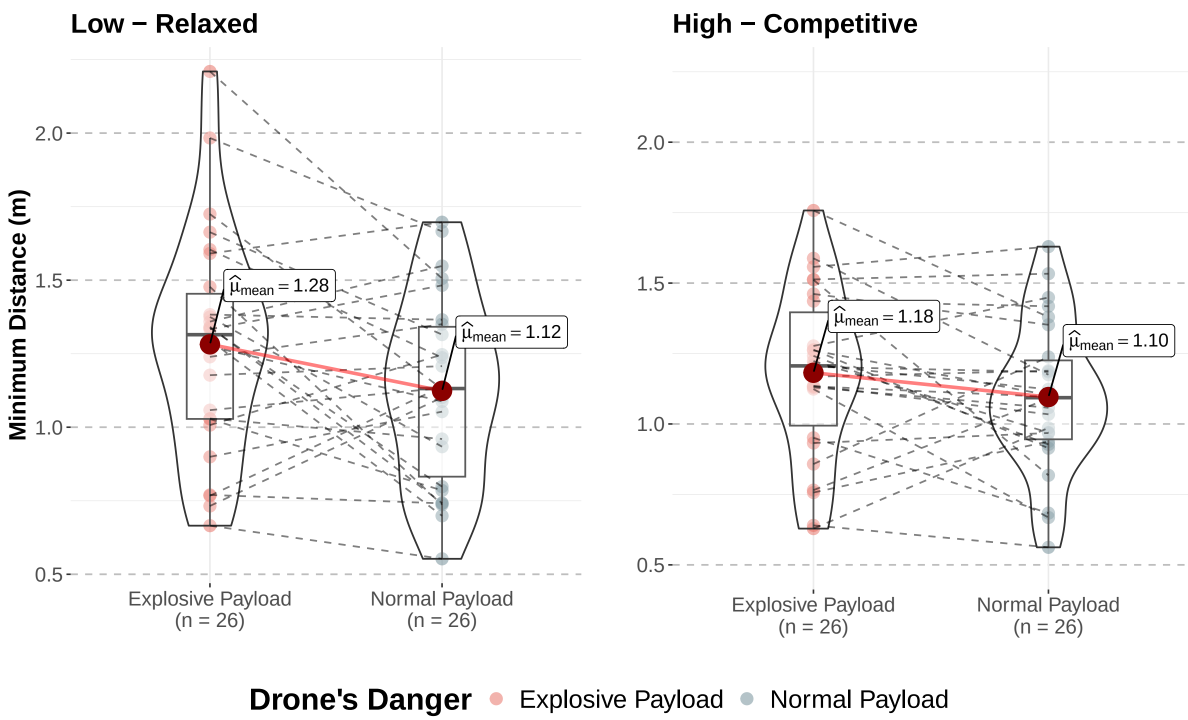


Figure 5.8: Boxplot and violin plots illustrating participants' minimum maintained distance from the drone across different conditions of *Task Priority* and *Drone's Danger*. Participants maintained a significantly greater distance from the drone when it carried explosive cubes compared to normal ones. Additionally, there is a trend of lower maintained distances and smaller differences between danger levels in the competitive condition, although statistical significance was not observed.

$9.54e^{-5}, ges = 0.21$). As shown in Figure 5.9, participants walked significantly faster on average ($p = 1.65e^{-4}$) in the competitive setting ($M_{Competitive} = 1.02m/s$) compared to the relaxed scenario ($M_{Normal} = 0.92m/s$). Similarly, peak walking speed was significantly higher ($p = 1.11^{-8}$) in the competitive setting ($M_{Competitive} = 1.58m/s$) compared to the relaxed scenario ($M_{Relaxed} = 1.39m/s$). Interestingly, participants' pace appears to be lower than the average walking pace reported in the literature (1.43 m/s; [49]). This variance can likely be attributed to the fact that the measurement was taken while participants were not actively walking. This explanation is further supported by the measured peak walking speeds, which are closer to the average walking pace found in the literature. Peak walking speeds may better reflect the pace at which participants are willing to walk, as they do not include potential pauses or acceleration/deceleration phases.

Correlations Both average walking speed ($r = 0.34$, $p = 0.013$) and peak walking speed ($r = 0.32$, $p = 0.021$) show moderate positive correlations with participants' self-reported stress. These correlations were more pronounced among participants who completed the relaxed scenario before the competitive one, with correlations of $r = 0.46$ ($p = 0.017$) for average walking pace and $r = 0.49$ ($p = 0.012$) for peak walking pace. However, these correlations were not statistically significant for those who performed the competitive scenario first. No other correlations were observed for either average or peak walking pace.

Finding 3 *Participants' pace significantly increases when the task priority is high.*

- As expected, participants walk significantly faster in the room under the competitive condition compared to the relaxed one. It's worth noting that the speed at which participants move affects the timing of their encounters with the drone. Given the findings of previous statistical tests, it's possible that participants capitalized on this difference in speed to more effectively adhere to the shortest path while maintaining a similar distance from the drone between the two scenarios. Further exploration of participants' navigation strategy was conducted during the interviews analyzed in subsection 5.4.4.

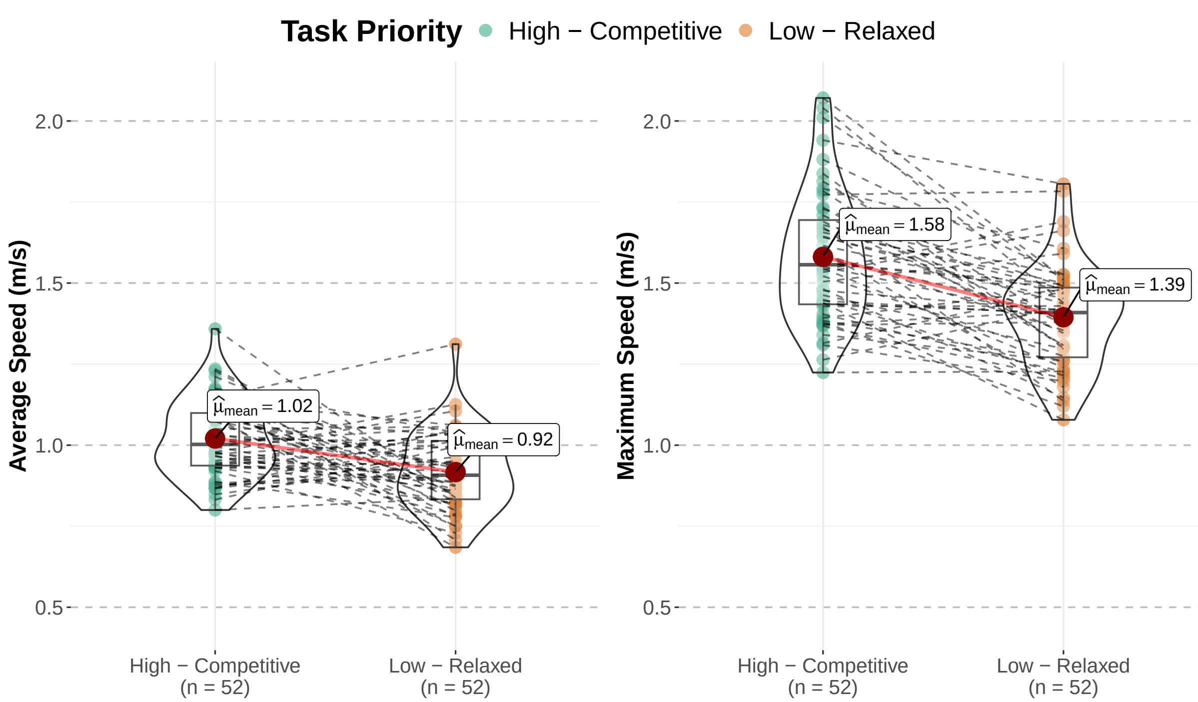


Figure 5.9: Boxplot and violin plots illustrating participants' average (Left) and maximum (Right) walking speed for each *Task Priority* conditions. The sample size for each Task Priority is 52, which results from 26 participants tested under two Drone's Danger conditions. Participants' average and peak walking speed are significantly higher in the High Task Priority condition compared to the relaxed one.

5.4.4 Qualitative Analysis

Proxemic Behaviours

During the interview, we initially inquired about participants' approaches to the situation and their strategies for performing the task while avoiding the drone. This was aimed at gaining insight into their thoughts during the process. Additionally, we asked where their attention was focused. Participants then discussed the general factors influencing the distance they maintained from the drone. Finally, we delved into the impact of explosive boxes and the two scenarios on these various aspects.

Processes of Avoiding the Drone When queried about their thought process or strategy for reaching their objective while avoiding the drone, participants presented a variety of approaches. Notably, many participants emphasized the importance of projecting the drone's path from its initial direction, with ten of them basing their strategy on this factor. Among them, five participants opted to take an alternative route, while one preferred to delay their actions until after the drone passed, and another participant chose to wait for the drone to clear the area before proceeding. However, these strategies heavily rely on the drone's flight behavior. When asked how their approach would change if the drone did not follow straight lines, P8 expressed concern, stating, "it would be very scary if it's difficult to guess where it's going," and P13 explained, "it would have made a difference because I wouldn't be able to say if he was actually coming towards me or if he was changing. So that would make me actually need to constantly see him and see where he's going." Interestingly, although beneficial in aiding participants in deciding their future actions, incorrect projections may occur, as reported by P8: "I was guessing the way that the drone will come and I guessed it wrong," which could have detrimental effects.

Additionally, two participants reported periodically checking the drone's position, while two others remained consistently aware of its whereabouts to avoid collisions. Similarly, two participants relied on the sound of the drone to gauge its location and movements and adjusted their actions accordingly.

Four participants took a proactive approach, realizing they could outpace the drone and expedite their task completion to avoid encountering it in the middle of the room. For example, P19 stated, "I tried to walk faster so I could avoid it. So I was working faster to not collide with it," while P24 mentioned, "I could just walk faster and finish the task before the drone so we wouldn't meet in the middle of the room." Leveraging the drone's moderate speed, P25 described following the shortest path and making last-minute adjustments if necessary, stating, "if I had to move towards the same area where the drone is, I would go straight ahead. I was thinking that maybe at the last moment I have the chance to change direction."

Conversely, two participants did not employ specific strategies but relied on intuition. For instance, P7 remarked, "I just wanted to find the box as soon as possible. I just do my own thing naturally. But I also let the drone do its own thing naturally. So everything is kind of natural to me." Similarly, P1 likened the experience to avoiding obstacles in everyday life, stating, "it's like avoiding a human. It's like avoiding anything coming at you. You want to have some space like not being too close but not being too far because you want to be efficient."

These diverse strategies illustrate the array of behaviors exhibited by participants, with some devising plans based on a clear understanding of the situation, while others improvised in real-time, leveraging their mobility to proactively navigate the environment and achieve their objectives before encountering the drone becomes an impediment.

Participant's Attention When queried about where their attention was focused during the study, most participants (17) instinctively responded that their primary focus was on locating the boxes and determining where to drop them. Some (5) elaborated by mentioning that after retrieving the cube, they checked the drone's position to confirm their route before shifting their attention back to the task at hand, aligning with the projection strategies described earlier. Conversely, others described a shared focus on both locating the cube and monitoring the drone throughout the task, maintaining awareness of both elements simultaneously. Only a minority of participants initially reported focusing on the drone itself.

Interestingly, while vision appears to have been the predominant sense utilized throughout the task, the sound of the drone emerged as a useful auditory cue, with nine participants reporting using it to locate the drone and discern its movements. Participant P21 described the sound as "very lifelike" and remarked, "I think it was quite useful. I could hear it coming closer." Conversely, three participants explicitly stated that they did not pay any attention to the sound, with P18 noting, "it was just easier to look at it." However, the sound also garnered negative feedback, described as distracting or potentially misleading. Participant P18 expressed, "the noise was prevalent. I wish it was quiet. It would probably make me more focused on the action of picking up these blocks." Similarly, P9 remarked, "I always feel like we're closer. I was trying to find where the drone actually was."

Factor Influencing Maintained Distances We proceeded to inquire about the factors that influenced the distance participants maintained from the drone. Predictably, the presence of the explosive payload emerged as a significant factor affecting distancing behavior, with seven participants explicitly noting its direct impact on their distance from the drone. For instance, participant P12 mentioned, "I was more likely to take much larger curves so that I stayed further away from the red boxes."

Additionally, four participants mentioned their primary motivation was to avoid colliding with the drone. The dynamic sound emitted by the drone was highlighted by three participants as an influential factor, serving both as an indicator of its proximity and as a gauge of its perceived threat level. Interestingly, participant P25 mentioned that once they understood the drone's predictable path, they felt comfortable moving closer, reasoning, "It's not going to make any sudden moves towards me. If I know that it's going towards a direction, even if I'm close, I'm like, I know that you're doing your course. I'm doing mine. That's fine."

Moreover, participants indicated that the destination they needed to reach was a significant factor influencing their approach, with seven participants specifically mentioning it. In the competitive setting, urgency played a prominent role, with five participants noting its influence on their behavior. For example, P20 remarked, "you just tend to focus on your tasks, so you really don't care [about the distance]. Especially when your time is running out. So you just try to move like, I know you're close, but I'm going to move anyway because I really don't have any choice. So you're just like squeezing and try to run straight." Similarly, P1 mentioned, "in the competitive scenario I took more risks in taking the shorter path knowing the drone is coming my way."

Managing Danger

We specifically inquired about how the presence of explosive cubes influenced participants' approach and behavior in the situation. From an attentional standpoint, five participants reported heightened attention to the drone when it carried the red cubes, with P4 noting, "they did alert my attention." Interestingly, another subset of three participants mentioned disregarding the cubes entirely, exemplified by P5's comment, "I almost ignored the red boxes."

In terms of behavior, two distinct groups emerged. One group acknowledged the presence of the cubes and adjusted their behavior accordingly due to the perceived increased threat, while the other group believed no specific actions were necessary. Among the latter, five participants stated that avoiding collision with the drone automatically meant avoiding the red cubes, making specific adaptations unnecessary. For instance, P4 mentioned, "I was already avoiding crashing with it when it didn't have the red box," and P15 stated, "I was not focusing on what box it was carrying because I was only focused on avoiding the drone, whether it carried a normal regular box or a red box."

Conversely, among those who reacted specifically to the explosive cubes, seven participants maintained greater distances, two occasionally stopped and waited, and one slowed their movements. Notably, while one participant (P1) admitted to risking their safety due to the competitive setting, stating, "if the time is close to 10 seconds, at that time I would take more risk going the path that I would even if the drone is carrying the red box," another prioritized safety over speed, as expressed by P3: "I was more worried about the explosion than the time. Our task was time-based, so I needed to do it as fast as I can. But I was more worried about the explosion than the time. So yeah, the red boxes were one of the major causes for my worry or stress," highlighting the diverse performance-to-safety trade-offs observed among participants.

It's noteworthy that apart from the presence of explosive cubes, participants also noted that the drone's behavior itself, such as its direction and proximity, seemed to impact their perception of threat. Two participants mentioned adjusting their behavior based on how close the drone was and which direction it was moving. For instance, Participant 6 remarked, "If it was on the opposite side of the room, not too much to worry about. If it's 3/4 of the room still OK, if it's half maybe I start considering more. Then once it gets like second-half, almost getting closer. It's like more urgent triggers in my head."

Impact of the Scenarios

We concluded by querying participants about any behavioral changes between the first and second scenarios, particularly focusing on the influence of the competitive setting.

Urgency Feeling A notable observation was the heightened sense of urgency reported by many participants (9) during the timed competitive scenario. This increased urgency often correlated with the most frequently reported behavioral change (8), which was an escalation in walking speed in the competitive setting.

Another intriguing pattern emerged from participants' responses, potentially linked to the increased mental demand induced by the sense of urgency. For some individuals, the high Task-Priority condition appeared to impose too great a mental burden to allow for precise adjustment of their distance from the drone. Consequently, they maintained a larger, less calculated distance, which, although potentially less efficient, was compensated for by increased walking speed and, notably, required less mental effort. For instance, P18 remarked, "I think maybe I tried to avoid the drone more in the second [Competitive] part. Like, in the first one, I was like, 'Oh, it's fine. It's beside me. But I'll just walk past, and it'll be alright.' But in the second one, I was like, 'No, I have a job to do. I need to get this done, and there's no time for this.'" Similarly, P20 described their strategy in the second scenario as "just like, don't collide into it. I have enough pressure on me. Just move around."

Task-focused Additionally, 8 participants noted that the scenarios altered their focus. P20 remarked that in the relaxed scenario, "I was relaxed, I was doing my thing I was just having fun," while "the moment there is a deadline or have to do this in this time, then there is a sense of pressure." Similarly, P19 noted that "in the first [relaxed] one, I was just like, I have to do it that's it. There was no hurry. No rush," whereas "in the second [Competitive] scenario, I was a little competitive because I was doing it with him. So it felt like a competition. I felt like I should work fast. So I started moving fast." P8 simply remarked, "It was like different focus for different round."

This change in focus was often accompanied by a shift in attention, with 5 participants reporting allocating less attention to the drone and instead focusing more intently on the task. P12 explained, "Because of the time constraint once I knew the drone was going that direction, I didn't need to bother about the drone. I can just go straight to my location." It even resulted in one instance where a participant missed spotting explosive cubes. P1 recounted, "Yeah, most of the time I was focusing on the location of the glowing box because it's quite hard for me to look for the box...Especially in the time limit setting. Competitive setting. Yeah. I think there was one occasion I totally missed the drone carrying the red box. I noticed it when it went past me. I lost the attention of the drone and the red box," suggesting a heightened level of task-focused attention akin to tunnel vision.

Furthermore, some participants mentioned modifying their route to optimize reaching their destination, such as P12, who remarked, "I think I followed the shortest path more in the competitive setting than the relaxed setting. Relaxing, I had more time to just go around better settings, and you have to get there quickly because of the timer." Similarly, P1 noted, "Because in the competitive scenario, I took more risks in getting the shorter path given the drone is coming my way."

Lasting Competitive Effect A minority of participants (4) noted that the change in scenarios had no apparent impact on their behavior, with the competitive scenario having a lasting effect on the relaxed scenario. Notably, P7 remarked that after experiencing the timed scenario first, they approached the second one similarly, stating, "because I had seen the timer in the first one, so even in the second one, I still felt I was competing with the drone. I was still trying to get it done fast." Similarly, P15 mentioned maintaining a sense of urgency during the relaxed scenario, expressing, "in the second case, I was moving closer to the drone to, you know, minimize my distance and get it quicker. I know it was not time-based, but still, I chose to move much closer."

Increasing Understanding An interesting phenomenon was the increased ease participants experienced from the first scenario to the second in co-existing in the room with the drone, with 8 participants reporting a better understanding of the drone's behavior and how to approach it more effectively. P11 said, "I kind of got used to the drone being in the environment. I could, you know, focus on the task completely rather than consciously trying to avoid the drone at all times."

Virtual Reality Experience

We asked participants questions to further examine the validity our approach to study human behaviours around drones in VR. Consistent with the considerations outlined in subsection 5.3.1 to enhance ecological validity, we specifically investigated whether participants' behaviors concerning the drone or their task performance were influenced by the VR environment. Overall, participants' feedback suggests that most individuals would have behaved similarly, although some would have been more cautious due to the potential physical consequences. Additionally, participants easily interacted with the cubes and comfortably navigated the room, indicating that the VR setting did not hinder their task performance.

Behavioural Differences with the Real-World Initially, participants were asked to reflect on whether they would have acted differently if they had participated in the study with a physical drone in a real-world setting.

The majority of respondents (N=12) indicated that their behavior would have been similar in a real environment. For instance, P15 praised the accuracy of the VR replica, stating, "I'd never bothered about, you know, like I will dash into the tables. It was very real." However, some participants expressed potential differences, with P8 mentioning they would still "be more anxious." This sentiment aligned with the second most common response, as N=7 participants stated they would exercise extra caution and be more attentive to the drone, citing concerns about the real physical consequences of potential collisions. Only two participants acknowledged potential behavioral changes, with P1 indicating they "would stay further away from it because I know it's kind of fragile. I mean, I can get cut like an actual cut from getting close to the drone," and P25 suggesting they might "be more aware and slower." Furthermore, three participants provided feedback suggesting that their perception of their surroundings would be clearer in the real world, facilitating distance estimation. Interestingly, P16 remarked, "I know my body dimensions, know how big I am or how long my arms are so I am just keeping my body out of the direction of the drone," highlighting the role of proprioception in effectively avoiding the drone in the absence of a visible body.

Interaction and Navigation To evaluate how the environment influenced participants' task performance, we also investigated any challenges they encountered while interacting with the cubes or navigating the environment. Their feedback suggests an overall ease in cube interaction, consistent with our direct observations during the study. For instance, P25 described it as "really easy," while P11 noted, "It was pretty smooth and interactive." Although two participants initially struggled with button confusion, this issue was resolved during the training session. Additionally, all participants expressed comfort while walking in the virtual environment, praising the accurate mapping of the room and the presence of real tables at the corresponding locations in the virtual environment. However, one participant reported feeling slightly nauseous upon removing the headset, despite feeling comfortable during the VR experience.

Envisioning Working with Drones

Drawing from their recent collaboration experiences with an autonomous drone, participants reflected on potential enhancements and envisioned changes that could facilitate their deployment in various working environments. Their insightful propositions span across several categories: Drone Design (including aspects such as appearance, sound, and physical safeguards), Flying Behavior (fly higher, self-regulate distances), Drone Communication (proximity indicators, directional and speed indicators), Working Space Configuration (dedicated area for people and drones) and Human Factor (explain the drone's behaviour beforehand).

Drone Design Participants offered suggestions for modifying the drone design, with 11 individuals specifically addressing the issue of sound generated by the operating drone, deeming it a significant auditory nuisance. Recommendations were put forth to either minimize the sound or alter its character, as it can induce discomfort or trigger negative associations. For example, participant P9 remarked, "it's either a bee or a fly. Whenever you hear those insects you don't like to hear them. You feel like you're threatened." Another participant echoed this sentiment, proposing that reducing the drone's sound level would mitigate its perceived threat. Nonetheless, participants recognized the practicality of the sound in locating the drone and proposed finding a balance between an acceptable disturbance threshold and its functionality. Expanding on the insect association, the same participant remarked, "it should look less like an insect [...] like something that you look at and you don't feel disgusted by it or you don't think about another item," suggesting that having no association is preferable to evoking negative ones. Moreover, regarding its appearance, one participant suggested enhancing the drone's visibility, such as by coloring it. Finally, two participants advocated for the addition of protective features that would ensure collisions are benign by design.

Flying Behaviour The flying behavior of the drone emerged as a significant area for potential enhancements, with four participants suggesting that it should fly at an adequate altitude to allow individuals to pass beneath it comfortably. Additionally, four individuals emphasized the importance of collision avoidance, while two participants highlighted the necessity for the drone to maintain an appropriate distance to ensure safety or minimize the stress induced by its proximity. Participant P12 further suggested that the drone should possess the capability to maneuver away from obstructions autonomously. These insights regarding spatial distances indicate that the drone should possess the ability to self-regulate its position relative to surrounding workers, prioritizing their safety, well-being, and operational efficiency. Two participants suggested the drone should either stick to the same flying paths, or keep this straight line behaviour because, as P13 said "it would follow the same path everywhere it goes and everyone would know that [...] it would be more convenient." And according to P24 "it's more efficient because everyone doesn't need to do some extra work. [...] it's easier for the human being." This notion of minimizing the effort required for people to understand the drone current and future states to adapt their own behaviour appears at multiple level of the study and is an important point which is discussed later in the paper (see section 5.5).

Drone's Communication Participants also suggested enhancing collaboration in this interaction context by implementing communication mechanisms for the drone to convey useful information to surrounding users. Six participants specifically proposed the use of auditory cues to alert users to the drone's imminent proximity, such as emitting a "beep" sound (mentioned by P16 and P6) or verbally communicating phrases like "Be careful, I'm going your way" (suggested by P5). This feature would be particularly beneficial in situations where users do not have visual contact with the drone, as noted by P6, who highlighted occurrences when the drone was positioned behind them during the study. By employing auditory cues, the drone could effectively capture users' attention and facilitate more prompt reactions. Additionally, P21 suggested that it would be advantageous to increase the drone's salience, especially when carrying potentially dangerous cargo like the explosive box, to better alert users who may not be visually aware of the danger. Two participants proposed another useful information for the drone to communicate would be its direction, aiding users in planning their movements. P6 suggested, "a color indicating which direction it's going [...] showing the predicted movement of that drone. That can point to you which way to go, how to plan your journey around this drone, so that you're more aware." In line with providing necessary information for trajectory planning, P6 also suggested visually indicating the drone's speed. Finally, two participants mentioned the potential for communication for entertainment purposes. P20 suggested, "it could talk to me, I guess. [...] I wouldn't mind when I'm doing my tasks, it's fun. So instead of just the fan, maybe to talk, make a conversation." This highlights the potential for drones to not only convey functional information but also contribute to a more engaging and enjoyable user experience.

Working Space Configuration Taking into account the environment in which both entities operate, four participants suggested allocating separate working spaces or pathways for the drone and workers to carry out their tasks independently, minimizing encounters and potential disruptions. Drawing a relevant parallel, P3 likened this approach to the design of streets, which have lane divisions for cycling, cars, and pedestrians, allowing each actor to function optimally without interference.

Human Factor A participant underscored a critical aspect of human interaction with autonomous machines: ensuring that individuals' mental models align with the actual behavior of the machines. P16 elaborated on this point, emphasizing the importance of employees understanding how drones operate, especially in high-risk environments such as factories. They explained, "I feel that if it's in a factory setting or something where there's a higher risk, employees should know how the drones work because this drone [in the study] have kind of a linear trajectory, kind of basic in its programming, so you didn't have to worry that much. But if the drone is going to perform more tasks, it's going to move more in different directions. There is a higher likelihood of someone getting injured, so I'd say getting everyone familiar with how the drone works." Essentially, before deploying drones in a work environment, it is crucial to explain their behavior to ensure that individuals have the correct mental model.

5.5 Discussion

5.5.1 Task's Impact on Human-Drone Proxemics

In this Chapter, we uncover the influence of goal-oriented behavior on human-drone proxemics, illustrating the behavioral adjustments that can occur under varying task-priority conditions and their impact on defensive responses.

Safety/Performance Trade-Off It's intriguing to note that our initial expectation, that an increased focus on task priority would detract from prioritizing defensive behaviors, was challenged by our findings. Across both relaxed and competitive conditions, participants consistently maintained a greater distance from the drone when it carried explosive boxes, which aligns with our previous research emphasizing the role of the defensive proxemic function in HDI [57, 59] (see chapter 4, subsection 4.6.1). However, this only partially aligns with our expectations, as we anticipated a significant reduction in defensive distancing in the High task-priority condition. As elaborated in subsection 5.5.2, this outcome could be attributed to individuals regulating their arousal levels. With the heightened arousal induced by the performance pressure and time constraints of the competitive scenario, participants lacked the mental resources to manage the additional stress of a close-range threat. As a result, they opted to maintain a greater distance, even though getting closer could have improved their performance.

Nonetheless, while defensive behaviors remained largely unchanged, their negative impact on performance was significantly minimized. In fact, participants not only adhered more closely to the shortest path in the competitive setting, but the pronounced increase in deviation caused by the drone's explosive payload in the low task-priority condition became negligible. Participants likely recognized that they could effectively navigate the room while avoiding the drone by adjusting their walking pace, as evidenced by the increased pace observed in the competitive setting and participants' feedback. These adaptive behaviors underscore the influence of goal-oriented behavior on individuals' navigation around an autonomous drone.

Although participants in our study had the chance to avoid the safety/performance trade-off, it raises questions about scenarios where such options are limited, forcing individuals to decide. Our research offers valuable insights into this aspect, as some participants felt compelled to make a trade-off and appeared to believe that assuming greater risks was their only option, indicating a preference for goal-oriented behaviors. This notion is supported by the negative correlation observed between participants' self-rated drive to perform the task and their minimum maintained distance from the drone. This observation holds significant implications from a research standpoint, as goal-oriented behaviors might overshadow the effects of experimental variables under study and influence the observed behaviors. In particular, if closer proximity to the drone can impact participants' task performance, experimenters should carefully consider task priority as a potential confounding variable.

Ultimately, our study reveals a spectrum of behaviors, but a general recommendation would be for drones operating in performance-focused environments to intentionally maintain a distance greater than what is considered comfortable for individuals. This approach serves to mitigate potentially risky behaviors associated with high task priorities, such as getting too close or failing to identify dangers, while also facilitating efficiency by allowing individuals to adhere to shortest paths, potentially at a reduced walking speed to minimize physical workload when trajectory adjustments are unnecessary due to the presence of the drone.

Lasting High Task Priority Effect An intriguing observation from our study is the enduring impact of high task priority, even in subsequent relaxed scenarios. Our findings indicate that following exposure to the competitive condition, some participants maintained a performance-focused mindset during the relaxed scenario, influencing their approach towards the drone. This is substantiated by the order effect identified in the manipulation check (see subsection 5.4.2) and participants' feedback. It suggests that high task priority can persist, shaping individuals' behaviors even in ostensibly relaxed situations, based on their previous experiences and activities.

5.5.2 Workload and Arousal Regulation

Mental workload appears to be a major factor to consider when performing tasks in a shared space with an autonomous drone, and can be linked to the arousal regulation function of proxemic behaviours [11, 122, 282].

Overwhelming Pressure An intriguing observation from this study is the potential impact of high mental workload associated with the competitive setting on human-drone proxemic distances. Previous research has shown that as the drone moves closer, the perceived threat increases, along with the perceived cognitive resources required to manage or evade the threat [59]. This is consistent with the feedback from participants, who expressed a growing sense of urgency as the distance between them and the drone decreased (see section 5.4.4). With the additional mental strain induced by the task in competitive settings, as evidenced by participants' feedback and a significant increase in self-reported stress, it appears that some individuals lacked the cognitive capacity to handle situations of close proximity with the drone. Consequently, they report having opted for a larger, less calculated distance, which, despite potentially being less efficient would require notably less mental effort, and could be compensated for by increased walking speed.

Given the arousal regulation proxemic function, which posits that individuals modulate their distance to prevent overstimulation (e.g., sensory overload [122], arousal [11,282]), it's plausible that the competitive setting heightened contextual stimulation. This increased stimulation may have narrowed the range of stimulation individuals were willing to tolerate from the drone, prompting them to adjust their personal space to align with this revised acceptable range. Prior research in Human-Robot Interaction (HRI) has explored the effects of mental memory load on the comfortable stop distance. While they expected results similar to ours, no significant impact of working memory load on participants' comfortable distance was observed [226]. It's worth noting that the methodology employed, the stop-approach procedure outlined in section 5.2, might not have allowed participants to demonstrate natural behaviors, particularly since they did not have to actively manage the drone's presence as participants did in our study.

While this study offers intriguing insights into the influence of mental workload and arousal regulation, our findings only partially support this hypothesis, as we did not observe a significant difference in maintained distance between the High and Low Task-Priority conditions. This could be attributed to the counteracting influence of goal-oriented behavior, which tended to encourage closer proximity between participants and the drone. While the explanation provided may align with the behavior of some participants, it does not fully account for the behaviors of all participants. Future research could delve deeper into the arousal regulation function in human-drone interactions, with potential avenues of exploration including the role of auditory cues emitted by the drone.

Mental Model According to participants, their mental model of the drone behavior influenced the mental effort required for them to navigate the room safely and effectively. Apart from the scenario's impact, several participants noted that their enhanced understanding of the drone's behavior from the first to the second round influenced their approach to the situation. Specifically, they appreciated its movements in line, which allowed them to predict its future position easily and move around it confidently, knowing it wouldn't suddenly change course. While the drone's simple behavior lacked the ability to dynamically avoid participants or adjust its trajectory on the fly, it simplified participants' interpretation of the information they received, and their projections could endure until they reached their destination.

This prompts consideration of whether more complex behavior would offer benefits. For instance, avoiding users might introduce uncertainty about whether the drone will evade participants to the right or left, potentially leading to collisions similar to those when two people approaching each other on the street can't decide how to avoid each other. It is crucial to note that explaining the drone's behavior beforehand is advisable to ensure that users correctly interpret its cues and react appropriately.

5.5.3 The Fundamental Role of Attention

In a drone encounter, the initial step towards assessing the level of threat is the perception and interpretation of sensory inputs, which subsequently influences people's behavioral response [59]. Consequently, the allocation of attention by individuals plays a pivotal role in this process, highlighting the importance of comprehending its utilization in Human–Drone Interactions.

Dynamic Allocation Our findings indicate that participants primarily focused on their task, with some attention also directed towards the drone which aligns with previous attentional measurements in Human–Robot collaborations contexts [232]. Interestingly, participants reported heightened awareness when the explosive box appeared, consistent with previous explanations suggesting that attention to a threat increases with its intensity [44, 59, 133]. Prior studies have emphasized how drones can distract workers from their tasks and surroundings on construction sites [15]. Our results suggest that this distraction could be amplified when drones carry potentially hazardous objects. Furthermore, participants demonstrated a dynamic allocation of attention in high task-priority conditions. While their primary focus remained on finding task-oriented information, they directed more attention to the drone at specific moments, such as when planning their route to the next location. This adaptive attention allocation enabled them to accurately assess the situation and level of threat, ensuring they could safely reach their objectives before returning their focus to the task at hand.

Prevent Out-of-the-Loop Syndrome This adaptive allocation of attention exemplifies what we view as the optimal balance between efficiency and safety. It acts as a precautionary measure against the "out-of-the-loop" syndrome, where individuals lack information about a system they are no longer actively engaged with and is often observed with autonomous systems. Despite programming drones to avoid collisions and implementing safety protocols, there's always a risk of malfunctions or human error. For instance, in a shared space a drone may unexpectedly enter an area designated for humans, or vice versa, necessitating reactions from nearby users. Without prior awareness of the drone state, individuals may be ill-prepared to respond effectively, heightening the risk of accidents. Therefore, it's crucial to maintain some level of awareness regarding the drone's current and future states in the shared space. Expanding on this concept, designers could improve this process by assisting users in perceiving and interpreting the relevant information needed to accurately assess the current and future situations, precisely when their attention is momentarily focused on the drone during the situation assessment phase. Future research could explore identifying the most effective form and content of such cues, with the optimal ones being those that are intuitively comprehensible, requiring minimal mental effort and attention from users while avoiding overstimulation. Participants recommended employing audio cues, lights, or vocal communication. Prior research has already investigated the use of drone movements to convey emotions [79] or intentions [42, 87, 344], as well as the use of lights to signal engagement intentions with people [149].

Attentional Tunneling However, some participants displayed an excessive fixation on locating task-related information during the competitive setting, suggesting potential attentional tunneling. One participant reported experiencing this phenomenon, which led to a loss of attention towards the drone and a failure to spot the explosive cube. While attentional tunneling can enhance performance when relevant information is within its focus [214], it also results in a disregard for external stimuli, significantly altering their perception of the situation and rendering them unaware of potential imminent dangers. Interestingly, previous research has demonstrated that task priority can induce attentional tunnels, causing operators to overly focus on tasks perceived as the most important [302], aligning with the increased task priority induced by the competitive scenario. When workers' attention must be directed towards the drone, such as when they need updates on its status (e.g., carrying a hazardous object, obstructing their path), and it appears that surrounding users are not attentive due to tunneling or contextual impairment (e.g., the drone is out of sight), the drone should take proactive measures to attract users' attention. For instance, it could emit a beeping noise, as suggested by participants. Autonomous drones might be able to recognise attentional tunneling through behavioural indices [214].

Auditory cues While participants primarily relied on visual cues to complete the task and track the drone's location, they also found auditory cues from the drone's sound to be helpful in complementing their visual perception, especially for detecting movement or proximity changes. Sound plays a significant role in Human-Robot Interaction (HRI) research, with studies demonstrating its utility in aiding users to locate robots during collaborative tasks when they are not directly visible [81]. However, the sound emitted by flying drones often carries negative connotations and is perceived as threatening [59]. Furthermore, the acoustic properties of drone sound tend to be more bothersome compared to other common technological sounds encountered in daily life, such as those produced by cars [85]. Several participants also commented on this aspect, suggesting that modifying the drone's sound could enhance the collaborative experience, which suggests a promising avenue for future research. Nevertheless, controlling sound in real-world settings for experimental purposes presents challenges, with the noise produced by drone flight often masking potential acoustic communication opportunities, as emphasized in [234]. Virtual Reality (VR) emerges as a viable solution for addressing these challenges, offering a controlled environment to explore acoustic interactions. Building on our findings, future studies could delve into how the operational sound of drones influences individuals' mental workload and proxemic behaviors in work environments.

5.5.4 Studying Human–Drone Proxemic in VR

By leveraging VR technology, we were able to design a theoretically informed experiment that simulates real-world interactions between humans and drones while maintaining control over experimental conditions.

Validity Participant feedback in section 5.4.4, coupled with their high reported presence and minimal cybersickness, attests to the quality of our simulation. Building upon the methodology outlined in our previous work [59] (see chapter 4), where no significant disparities were found between real and virtual environments in a drone proxemics study, we consider that participants behaved naturally in our study, with minimal influence from the VR environment. While it might be anticipated that maintained distances would generally be greater in a real-world scenario notably due to the real consequences of a collision with the drone, we can reasonably infer that the observed effects in our study would translate to a real-world experimental setting.

Novel Metrics The utilization of VR allowed us to collect novel measurements tailored to the specific requirements of our investigation subsection 5.3.2. As demonstrated in the preceding discussion sections, these measurements proved instrumental in uncovering behaviors that may have been overlooked or misinterpreted if we had relied solely on conventional metrics such as minimum measured distance. We hope that our work will inspire researchers to employ this powerful tool in their own investigations and incorporate additional relevant metrics to deepen our understanding of observed proxemic behaviors.

Untapped potential There remains untapped potential in the use of VR for human-drone interaction research. One promising avenue is the exploration of novel drone designs, communication cues, and interaction techniques that may be too complex or impractical to implement in real-world settings. In the virtual realm, researchers have the freedom to experiment with these elements without logistical constraints, opening up new possibilities for innovation and discovery in the field of human-drone interactions.

5.6 Chapter Conclusion

In this chapter, we explored how contextual factors related to the tasks individuals perform around a drone influence their proxemic behaviors, particularly when another proxemic function is also at play. Our investigation sheds light on the role of goal-oriented behaviors in human–drone interactions and how these behaviors may interact with other driving mechanisms. Given the importance of individual safety, we examined how goal-oriented behaviors might affect the defensive proxemic function to identify any potential risks.

Immersed in the virtual environment (whose design is detailed in subsection 5.3.1), participants and a drone engaged in tasks requiring the movement of objects between different locations, operating under two *Task Priority* conditions: either *Low–Relaxed Scenario* or *High–Competitive Scenario* (see section 5.3 for details). By controlling the objects to be relocated and their designated destinations, we orchestrated encounters between humans and drones (see Figure 5.3), thereby observing natural proxemic behaviors in a setting where both entities autonomously pursued their respective objectives (RQ1). To assess the influence of goal-oriented behaviors on the defensive proxemic function (RQ2), we introduced varying levels of risk, labelled as *Drone's Danger*, associated with the drone's cargo. Specifically, the drone transported either ordinary, harmless boxes (*Low–Normal Cube*) or hazardous red boxes (*High–Explosive Cube*), which triggered an explosion upon contact with the participant. Leveraging this unique setting and utilizing the capabilities of the virtual environment (see subsection 5.3.1), we expanded conventional proxemic metrics, such as minimum distance, to include novel metrics like participants' walking speed and deviation from their shortest path (outlined in subsection 5.3.2). This novel methodological approach allowed for a more comprehensive understanding of individuals' proxemic behaviors.

In summary, our research illuminates the significant impact of goal-oriented behaviors on the spatial dynamics of Human-Drone Interactions (HDI), particularly in conjunction with defensive proxemic functions. Operating within environments where individuals and drones engage autonomously, we consistently observed participants maintaining greater distances from drones carrying hazardous payloads, even amidst high task priority scenarios. Yet, participants also exhibited adaptability in optimizing their trajectories and walking speeds to enhance efficiency, particularly in contexts of elevated task priority. An explanation for these findings may lie in the involvement of a third proxemic mechanism influenced by the Task-Priority condition: the arousal regulation function.

Our study highlights the significance of accounting for the psychological effects of the task at hand, as participants' mental workload and attention likely play key roles in shaping proxemic behaviors around drones. We encourage further investigation into these factors within HDI, especially regarding their impact on drone deployment in work environments.

Of significant concern is the indication of a potential trade-off between performance and safety, with some participants displaying a willingness to take greater risks or demonstrating inattentiveness to alerting cues under conditions of performance demands and time pressure. Additionally, a correlation emerged between perceived task priority and reduced distancing from drones, suggesting avenues for future research to mitigate such phenomena.

Furthermore, our study highlights the invaluable role of Virtual Reality (VR) in conducting valid, controlled, and safe research on human-drone proxemics. Leveraging the full potential of VR presents exciting prospects for advancing our understanding of HDIs and fostering innovation in this rapidly evolving field.

5.6.1 **Research Question 1.3 –** What is the role of the Goal–Oriented Proxemic Function in HDI?

The Role of the Goal-Oriented Proxemic Function

Goal-oriented proxemics refers to how people use physical space to achieve specific objectives within a given context. This includes actions such as navigation and adjusting distances in relation to their goals. These behaviors are a subset of broader goal-oriented actions aimed at accomplishing tasks. As drones increasingly operate in environments where people engage in goal-oriented proxemic behaviors, understanding the interaction between these behaviors and drones is crucial for designing drones that integrate seamlessly into daily life.

Given the demonstrated impact of goal-oriented behavior on how individuals navigate around drones in this chapter, it is crucial to incorporate this aspect into studies of human-drone proxemics. This chapter proposes a framework to examine how goal-oriented behaviors influence proxemic interactions with drones. This framework is intended as a practical tool for researchers focusing on human-drone proxemics, rather than as a comprehensive theory. For an in-depth theoretical exploration of decision-making processes, we recommend consulting the work of Icek Ajzen [12, 131].

Summary: In our framework, there are four key components: 1) the *goal* or target the individual is aiming for; 2) the range of *actions* available to achieve this target; 3) the *context* in which these actions occur and the *obstacles* that may impede the execution of these actions. Additional concepts of subjective *prioritisation*, *obstacle significance* and *sensory experience* explain differences among individuals as they may: 1) assign different levels of importance to achieving their goal versus addressing obstacles, 2) perceive the significance of obstacles differently (e.g., varying threat perception), and 3) be differently affected by the task itself, influencing how they perceive and experience the situation. Together, these factors shape how individuals subjectively evaluate the situation and determine their actions. **In practice,** researchers should clearly define the goal of the experiment to avoid ambiguity and ensure consistent targets for all participants. Once the goal is clear, researchers should determine if spatial strategies like navigation or adjusting distance are relevant. This assessment can reveal how goal-oriented motivations might influence participants' proxemic behaviors. Researchers must consider obstacles that might hinder these actions, including physical, social, safety, or well-being factors, whether they are intentional or not. After considering these factors, researchers can predict potential behaviors. Behavior varies based on how people see obstacles, balance overcoming them with reaching goals, and use their senses. While managing these aspects of the experience can be challenging, researchers can collect relevant information about participants before the study to anticipate potential variations. They can also assess these factors afterward to better explain behavioral differences. Techniques like questionnaires, direct questioning, eye-tracking, and post-experiment interviews can help researchers understand participants' priorities, attention focus, and interactions with the drone. Ultimately, while controlling for these variables can be challenging, adhering to this framework will help researchers provide an explanation of how goal-oriented behaviors influence proxemics in both direct and indirect human-drone interactions.

1) Goal Setting When individuals are faced with a goal, they first involve assessing the task's demands and their own capabilities, influenced by the nature of the goal and personal characteristics. It's crucial to distinguish between the goal as presented to individuals and the subjective target they set for themselves. Researchers should carefully consider this distinction and minimize subjective interpretation gaps to avoid variations in behavior stemming from different personal goals.

In practice when designing experiments, clearly define the goal or target that participants should aim for. This could be a specific task like reaching a destination, avoiding obstacles, or interacting with a drone in a particular way. Researchers should also consider how participants might set their own subjective goals and fill any gap of ambiguity of they want to avoid interpersonal differences.

Example: In our studies, we observed notable differences in how people approached tasks due to these subjective interpretations. For example, in Study #1, detailed in chapter 3, participants were asked to reach and touch colored papers in a room. Some participants, motivated by a desire to perform well, set high personal performance targets, which shaped their behavior differently from those who aimed for comfort without a focus on high performance. Similarly, in the study discussed in this chapter, participants were placed in a competitive environment with implicit instructions to outperform others, though they did not know their competitors' scores. This setup led participants to set varying performance targets based on their expectations of competitors' performance, resulting in different behaviors. These findings highlight how personal goals and expectations influence behavior, emphasizing the need for clear and consistent goal-setting in research design.

2) Range of Actions Once individuals have set their target, they often intuitively identify effective actions to achieve it. Specifically, the use of space—through navigation and distance adjustment—can be a proxemic action driven by the individual's goal, which we refer to as goal-oriented proxemic function. However, as with defensive behaviors, this is just one tool within a broader spectrum of actions that individuals may adopt to reach their objective.

In practice, once a goal is established, it's important to consider whether specific spatial behaviors might be a means for participants to achieve their goal.

Example: In a straightforward scenario, such as trying to reach point B from point A under time pressure in a controlled environment (as discussed in this chapter), the range of optimal actions is limited. The most efficient route is typically the shortest path, assuming no obstacles specific to the individual's circumstances (e.g., a person in a wheelchair may need to avoid stairs). Consequently, the most effective action involves a clear use of space: follow the shortest route and adjust one's pace. How strictly individuals adhere to this path and their speed—essentially, how they navigate the space—depends on the goal they've set, their perceived ability, the obstacles they encounter (e.g., a flying autonomous drone), and their personal priorities. For more complex goals, such as effective communication, individuals may encounter a broader range of potential actions. In these cases, they must assess what is necessary to be heard and understood, taking into account factors like ambient noise and the other person's hearing or comprehension abilities. Depending on their assessment, individuals may adjust their voice volume or distance, or take additional steps like moving to a quieter room or asking others to lower their voices. While goal-oriented behaviors can still be identified in these cases, they are part of a more complex set of potential actions, making it harder to predict whether they will play a significant role. Nonetheless, understanding these behaviors can be valuable for explaining proxemic choices in retrospect.

3) Identifying Obstacles Individuals rarely operate in controlled environments; real-world settings often present a range of complex and overlapping obstacles. Once a range of optimal actions are identified, they need to be adjusted to account for these challenges, which can include physical, social, safety or well-being-related factors. For instance, a physical obstacle might be a blocked pathway that requires finding an alternative route, a social obstacle could involve trying to communicate effectively in a library where maintaining a quiet demeanor is crucial to avoid disturbing others, a safety obstacle might involve avoiding a potentially hazardous area, a well-being obstacle could involve managing stress levels in a high-pressure situation, such as a tight deadline for a work project, where balancing work demands with personal health is critical.

In practice, researchers can adjust these obstacles to study how participants adapt their behavior. This is similar to our observation of how individuals manage an autonomous drone carrying hazardous objects while trying to achieve their goal through strategic use of space. Researchers should take into account the context in which actions occur and identify the potential obstacles individuals face. This approach helps narrow down the range of possible actions and predict the types of behaviors that may be observed, as illustrated by the strategies identified in our work, which are described below.

Example: In our research, the drone presented both a physical obstacle sometimes blocking the way, a safety obstacle as it carried explosive boxes that would explode upon contact, and a well-being obstacle with our findings suggesting that participants' arousal from the task itself introduced an additional challenge to maintaining the shortest path as elevated arousal diminished their tolerance for the added stress of the drone's proximity, which was perceived as a threat. Observing their various behaviours provided insights into different approaches people may use to address these obstacles:

- Finding Alternatives: Obstacles may necessitate finding alternative actions that still align with their goal. In our study, some participants opted to avoid the drone by adjusting their route and increasing their pace to maintain performance. This behavior represents an alternative optimal action where they adapted both their path and speed to meet their personal goals while addressing the obstacle. They were able to achieve their performance expectations, though with a modified approach.

- Reassessing Goals: When obstacles make the optimal action unachievable and no viable alternatives are available, individuals might reconsider their goals. Some participants chose safety over sticking strictly to the shortest path, leading them to select a less efficient route. This indicates a reassessment of their goals where safety became a higher priority than achieving maximum efficiency.

- Ignoring Obstacles: In other cases, individuals might choose to ignore obstacles to maintain efficiency. Some participants, despite the risks posed by the drone, decided to stay as close as possible to the shortest path, even if it meant minimal distance from the drone. This behavior demonstrates an extreme trade-off where efficiency is prioritized over safety, similar to someone who might disregard minor safety warnings or social norms to reach an important appointment as quickly as possible.

The differences in observed behaviors can be attributed to variations in how participants initially assessed the task's demands. Those who viewed the shortest path as the optimal strategy and saw deviations from it as a failure likely perceived a higher demand for high performance (or lower ability to increase their pace) compared to participants who adopted more balanced or alternative approaches. Even with the same goal, people may act differently due to various factors stemming from their subjective experiences of the situation, as discussed in the following paragraph.

4) Subjective Experiences Even with the same goal in the same context, people may act differently due to various factors. These include the subjective importance they assign to obstacles, how they prioritize these obstacles in relation to achieving the task, and how individuals perceive their environment and experience the task.

- **Significance of the Obstacles:** The significance of obstacles varies for each person due to different factors. Physical obstacles, for instance, may be easy for one person to navigate but pose a significant challenge for another due to differences in physical abilities. Similarly, the perception of threats can differ widely; some individuals may see a situation as highly dangerous, while others with different personality traits or levels of confidence may view it as less concerning. Social obstacles are also interpreted through a personal lens, influenced by cultural norms and individual experiences. Additionally, the capacity to manage well-being under pressure, such as handling stress or maintaining focus, varies among individuals, leading to different approaches and behaviors in the face of similar challenges. These subjective interpretations of obstacles play a critical role in determining how individuals evaluate the situation and respond it. It may notably play a role in the weight they give to managing them in opposition to taking the most optimal action.

  In practice, recognizing that individuals perceive and respond to obstacles differently enables researchers to anticipate potential variations in participant behavior. After identifying potential obstacles, researchers should consider the factors that might influence how significant these obstacles are to different individuals. By gathering relevant data before the study, researchers can better understand and interpret variations that arise from these confounding factors.

  Example: In our study, some participants were relatively unconcerned by the threat posed by the drone, perceiving little difference between when it carried explosive or harmless boxes. Others, however, viewed the explosive boxes as much more dangerous and responded with greater caution. This variation highlights how individual differences in obstacle perception can lead to different behavioral strategies, even in similar contexts. Although we collected demographic data, including participants' experience with VR—which could influence their perceived motor abilities in the virtual environment—none of these factors significantly impacted our results.

- **Prioritisation:** The concept of prioritization refers to how individuals balance the need to overcome obstacles against the importance of efficiently achieving their goals. When faced with obstacles, people may weigh these challenges differently based on their perception of the situation and the criticality of reaching their objective. This balancing act creates a sort of internal equation where the weight assigned to managing obstacles is measured against the urgency and significance of achieving the goal. This prioritization is not static; it can dynamically evolve as the situation changes. As the significance of obstacles fluctuates—perhaps due to increased awareness of a threat or a change in environmental conditions—so too can the importance assigned to addressing these challenges. Similarly, the criticality of reaching the objective might shift, influencing how much emphasis is placed on overcoming obstacles versus pursuing the goal directly.

In practice, understanding how individuals prioritize achieving their goals versus managing obstacles can offer valuable insights into their behavior. While this balance can be challenging to control, researchers can gain useful information by assessing participants' priorities through methods such as ratings and interviews.

Example: In our initial study in chapter 3, one participant noted that despite their significant fear of the drone and discomfort from being close to it, they chose to approach it closely to ensure efficient task performance. Additionally, in the current study, we observed a positive correlation between participants' drive to perform well and their reduced distance from the drone, highlighting how prioritizing efficiency can influence behavior. Conversely, some participants reported in interviews that they explicitly prioritized safety over efficiency, opting to maintain a greater distance from the drone even if it meant failing to achieve their target performance. This illustrates how the balance between safety and efficiency can shift, depending on individual priorities. Additionally, the dynamic nature of prioritization was highlighted in the current study, where some participants, when the timer exceeded 10 seconds and turned red, accelerated their pace and took greater risks to achieve their goal more quickly. This shift in priorities, driven by the urgency imposed by the time constraint, illustrates how changing conditions can influence the balance between managing obstacles and focusing on the goal.

- **Sensory Perception:** Depending on the task at hand, individuals must allocate their resources and utilize their senses to achieve their goal. For example, if someone uses their phone to check directions via an app, their sight is occupied, forcing them to rely more on their other senses, such as hearing. Additionally, how engaged individuals are with the task can greatly influence their sensory perception, often leading them to focus on specific sensory inputs while ignoring others, a phenomenon known as the tunneling effect.

In practice, researchers should look at how the task and its psychological effects influence how people perceive their surroundings. This, in turn, shapes their situational awareness, evaluation of obstacles, prioritization, and ultimately their behavior. Even if spatial strategies are not directly relevant for achieving the goal, the task can still influence proxemics by altering participants' perception of the environment and their evaluation of the situation. Researchers should anticipate such influences based on the task's nature and measure these effects by evaluating where participants focused their attention. This can be accomplished through direct questioning, using eye-tracking tools to monitor focus, conducting post-experiment interviews, and asking participants about their sensory engagement and management of the drone's presence.

Example: In our study, participants repeatedly identified glowing boxes in a room, which required them to use their sight. As a result, some individuals relied on the sound of the drone as a useful cue to detect its movement or proximity, since their visual focus was occupied. Because sight was essential for distinguishing between normal and explosive boxes, those deeply engaged in the task might have perceived the threat from the drone differently. Participants who concentrated on the shortest path often reported being so absorbed in the task that they did not notice the drone's proximity or the potential danger it posed. This intense focus may have led to a lower perception of the threat, making the drone's proximity seem less significant and less mentally demanding compared to those who remained more aware of the drone. Consequently, their reduced perception of threat influenced how they evaluated the drone's danger and managed their behavior.

5.6.2 **Contribution to Research Question 1.5 –** How do multiple proxemic functions interact in HDI?

Other Proxemic Functions (or Obstacles)

In our earlier discussion of goal-oriented proxemics, we referred to *obstacles* that individuals encounter while pursuing their objectives. Although these obstacles were framed within a goal-oriented context, they essentially represent other proxemic functions explored throughout this thesis, such as the communicative proxemic function (social obstacles) and the defensive proxemic function (safety obstacles). Our examination of goal-oriented proxemics in human-drone interactions has enhanced our understanding of how these various proxemic functions interact to shape overall proxemic responses. Additionally, the arousal regulation function (related to well-being) has not yet been explored in detail, though it may have significantly influenced some participants' proxemic behaviors in this chapter. Chapter 6 addresses this final function, focusing on how individuals manage sensory input overload while performing tasks with varying demands on working memory. This chapter offers insights into how people use space to regulate their arousal levels and examines the potential impact of drone deployment in work environments.

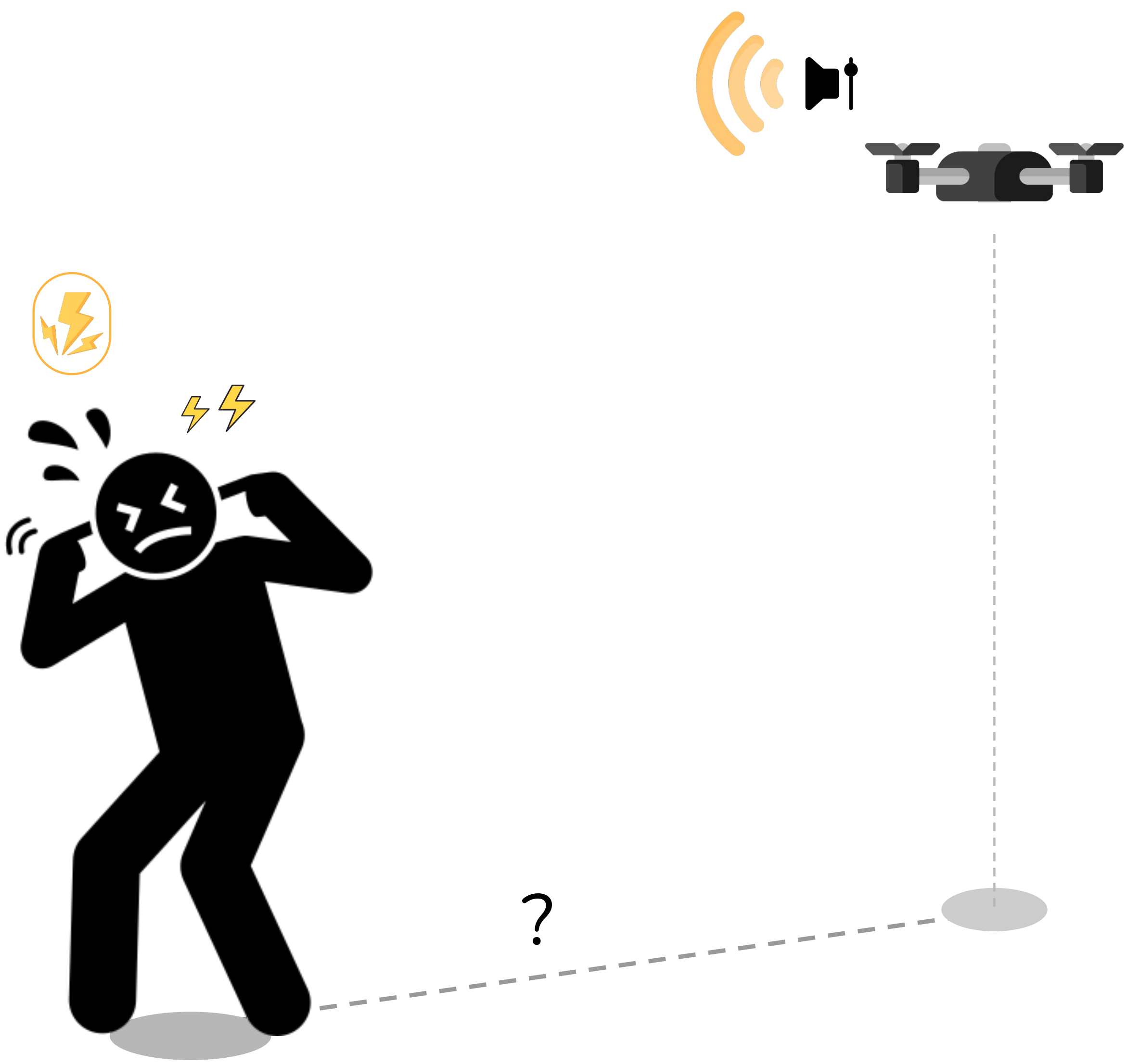
5.6.3 Contribution to Research Question 2 – How best to use VR to study human-drone proxemics?

Enhanced Proxemic Studies using Virtual Reality

In this chapter, we've explored the potential of Virtual Reality (VR) in advancing the study of proxemics, particularly by addressing the limitations of traditional metrics like minimum maintained distance. The use of VR allowed us to collect novel measurements tailored specifically to the needs of our investigation (see subsection 5.3.2). These measurements were instrumental in uncovering behaviors that might have been overlooked or misinterpreted if we had relied solely on conventional metrics. For instance, the VR setting enabled both the drone and participants to move autonomously, a scenario that would be challenging to replicate in the real world due to the complexity of drone programming, safety concerns, and issues of replicability. As demonstrated in the preceding discussion sections, VR unlocked a level of detail and additional aspects of proxemic behavior that provided a more comprehensive understanding of the dynamics at play. There is still significant untapped potential in using VR for human-drone interaction research. While chapter 3 explored innovative design approaches, the next chapter utilizes VR to manipulate aspects that are challenging to address in real-world settings, specifically the sound of the drone. This investigation aims to assess how varying levels of drone sound affect individuals' arousal and preferred distance during tasks with different working memory demands (see chapter 6).

Chapter 6

The Arousal Regulation Proxemic Function



6.1 Chapter Introduction

Arousal regulation involves managing one's physiological and psychological state in response to environmental stimuli [48]. In proxemics, individuals strategically use space to modulate their arousal levels: heightened arousal from stress or discomfort typically leads to increasing distance from the source [122], while positively valenced arousal, such as excitement or interest, encourages approaching behaviors [282]. After examining the communicative, defensive, and goal-oriented functions of proxemic behavior in human-drone interactions, we now seek to understand the role of arousal regulation in these dynamics.

6.1.1 Motivation

Why Assessing the Arousal Regulation Proxemic Function? Drones, with their intense sensory stimuli, are difficult to ignore. Their auditory and visual characteristics often require significant cognitive resources to process due to factors like loud noise [159], negative associations (e.g., resembling insects) [57, 59], or perceived threats (e.g., privacy concerns or physical safety) [59, 82]. With the potential for drones to elicit significant arousal, it remains unclear how individuals behaviorally respond to regulate these stimuli. One likely strategy for managing arousal is to dynamically adjust the distance between themselves and the drone.

Despite the potential importance of arousal regulation in shaping human-drone proxemic behavior, this area remains largely unexplored. Understanding how individuals respond to drone-induced arousal could help predict the impact of drones in various settings and inform the design of autonomous drones. This knowledge could lead to techniques for mitigating negative effects or, more optimistically, harnessing arousal-driven behaviors to achieve specific objectives, such as attracting or repelling people.

In this Chapter, we present a user study designed to explore how individuals adjust their spatial behavior in response to varying levels of arousal stimulation. We explain the rationale behind our choice of specific variables, which addresses existing gaps in human-drone interaction research and utilizes Virtual Reality to effectively tackle these issues, thereby amplifying the impact of our findings.

6.1.2 Overview of the Study #5: *"Exploring the Impact of Drone Noise Levels on Proxemics and Perception Across Different Working Memory Loads"*

Motivation A key aspect of drone design that may significantly impact arousal is its distinctive sound. Numerous studies report participant feedback highlighting drone noise as a major source of annoyance, and it has been identified as a critical design concern for social drones [38]. Research shows that drones emit a unique sound signature [1, 159], perceived as more annoying than aircraft, road traffic [85], or rail noise [256].

Since people often use spatial adjustments to avoid sensory overload [122] and regulate arousal [282], this auditory characteristic of drones presents an ideal opportunity to explore how sensory-based arousal stimulation from drone noise might influence proxemic behavior. Existing works offer insights into how drone sounds are perceived, but provide limited understanding of how individuals might respond behaviorally to these stimuli and their broader effects in specific settings. We address the following research question:

- **RQ1:** How do varying levels of drone noise intensity affect individuals' proxemic behaviors (distance maintained from the drone)? We expect that higher drone noise intensity will be associated with a greater distance maintained by participants, as they adjust their spatial behavior to manage arousal.

In addition, recent research [242] highlights that these studies often neglect the role of contextual factors and individual characteristics in shaping perceptions and responses. As discussed in the previous chapter 5, task demands may influence how much stimulation individuals are willing to tolerate, which could affect their tolerance of drone-related stimuli and influence the distance they maintain from the drone. This observation motivated our investigation into how varying mental memory loads, as a contextual factor, affect responses to drone noise. Accordingly, we address the following RQs:

- **RQ2:** How do task demands (mental workload) influence individuals' spatial adjustments and perceptions of drone noise? We expect that increased mental workload will result in a greater maintained distance from the drone due to higher cognitive demands, limiting the ability to cope with sound-related arousal stimulation.

- **RQ3:** How do individual characteristics, such as noise sensitivity, influence responses to drone noise in terms of proximity and arousal? We expect participants with higher noise sensitivity will maintain larger distances from the drone and report higher levels of annoyance and arousal compared to those with lower noise sensitivity.

To address: **1)** the shortage of observational studies on behavioral responses to drone noise, **2)** the need for deeper insight into how contextual factors affect the perception and impact of drone sounds, and **3)** the role of arousal regulation in shaping proxemic behavior around drones, we investigated how different levels of drone noise and varying mental workloads, linked to tasks of differing difficulties, interact to influence task performance, sound perception, and spatial adjustments.

Study Design & Methodology In our study, 30 participants were immersed in a mixed reality environment where they performed the n-back [190] task (i.e., identifying whether a current stimulus matches one presented N items earlier in a sequence) at two levels of difficulty (1-back vs 3-back) while exposed to a virtual drone emitting sounds at three different loudness levels (2x3 within-subject design). We collected data on their performance (reaction time, accuracy), psycho-acoustic metrics (perceived loudness and annoyance), threat perception, subjective arousal stimulation, NASA-TLX ratings, awareness of the drone and how participants were bothered by its presence. After completing the task at a fixed distance, participants were allowed to adjust their distance from the drone freely, indicating the distance at which they felt most comfortable continuing the task under the specific conditions.

Results The results presented in section 6.4 underscore the significant impact of drone sound intensity on individuals' spatial adjustment. Specifically, louder drone sounds were associated with increased subjective arousal and greater maintained distances. However, the interaction between drone sound and the task being performed revealed a more nuanced picture. Despite variations in sound intensity, no statistically significant differences in distance adjustments were observed between task conditions, challenging our initial expectations. This complexity is further explored through insights gained from post-experiment interviews, as discussed in subsection 6.5.5.

Perception of the drone sound was consistent with previous research, where louder sounds were perceived as more annoying and disruptive. Notably, our study provides the first empirical evidence that louder drone sounds are also perceived as more threatening. Similar to proxemics, the influence of the task on sound perception proved complex, with post-experiment interviews offering valuable insights, as detailed in subsection 6.5.1. Moreover, these interviews revealed the multifaceted nature of drone sound, which extends beyond mere acoustic features to function as an informational cue carrying various connotations, as discussed in subsection 6.5.4.

While the drone's sound did not significantly impact participants' objective and perceived task performance, it did alter their subjective experience. In particular, mental and physical workload, perceived effort, frustration, and pressure all increased with sound intensity, as explored in subsection 6.5.2.

Additionally, we found a significant correlation between participants' noise sensitivity and various measures of sound perception, underscoring the importance of individual differences in how drone sound is experienced (see subsection 6.5.3).

6.1.3 Chapter Structure

This chapter follows the same structure as the previous paper-based chapter. It starts with a related work section that reviews and synthesizes studies relevant to the investigation, offering the necessary background to understand the research gap, our approach, and the findings. Next, the methodology section details our approach to addressing this gap, including the use of a novel feature of recent Virtual Reality headsets (i.e., passthrough). Following this, we present both quantitative and qualitative results, continuing with multiple discussion points. The chapter concludes with a summary that encapsulates the objectives and main findings of our research.

Following this summary, we provide detailed responses to RQ 1.4, "What is the role of the Arousal Regulation Proxemic Function in HDI?" based on the findings. Additionally, we offer partial answers to RQ 2, "How can VR be effectively used to study human-drone proxemics?"

6.2 Related Work

This section provides an overview of the research landscape relevant to our study. We begin by revisiting the concept of arousal regulation, a function that, based on hints collected in previous studies, appears significant in shaping human spatial behavior around drones. Following this, we delve into the psychoacoustic properties of drone sound, exploring its potential impact on human perception and behavior, and review existing research on drone sound within the context of Human-Drone Interaction (HDI).

A comprehensive literature review of general proxemics, including human–drone proxemics and virtual reality, is presented in chapter 2. In contrast, this section narrows its scope to focus specifically on studies and related work that are directly relevant to the current investigation and the particular proxemic function under examination.

6.2.1 Arousal Regulation in Human–Drone Proxemics

Patterson [282] proposed that all interactions involve arousal, with changes in interpersonal distance triggering physiological responses that can be either positive or negative. As arousal intensifies, individuals tend to adjust their behavior: approaching sources of positive arousal and withdrawing from those that cause negative arousal. Extending this concept to non-social sources, Evans (1972) suggested that people maintain specific distances to regulate sensory input, keeping it below a threshold that could lead to sensory overload [122]. Given the sensory characteristics of drones—such as their striking appearance and loud sound—along with their often negative associations (e.g., perceived threats) [59, 82], it is reasonable to assume that encounters with drones generate some level of arousal.

Early in our research, we identified arousal regulation as a potential factor influencing people's proxemic behavior around drones. Although our primary focus was on other aspects, we consistently observed hints throughout our studies that suggest arousal regulation plays a role in shaping these behaviors. For instance, in two of our studies [57, 59], participants frequently cited the drone's noise as a significant source of annoyance, with some expressing a preference for maintaining greater distances. This behavior aligns with Patterson's theory, which suggests that when arousal becomes intense and negatively valenced, individuals tend to withdraw from the source of that arousal.

Furthermore, in the study presented in chapter 5, where participants performed a task under time and performance pressure, some reported that the increased arousal left them with insufficient mental resources to tolerate the additional stimulation posed by a close-range threat. This observation hints at a potential interaction between the arousal generated by the task context and that induced by the drone, particularly due to its perceived threat. In related work involving ground robots, Leichtmann et al. [226] examined the impact of working memory load on people's comfort distances. Although they did not find a direct effect, they observed that tasks with higher working memory loads led to increased emotional arousal, which in turn resulted in larger comfort distances. This further supports the potential role of arousal regulation in proxemic behaviors around robots and drones.

Research Gap While previous chapters extensively discuss the defensive (see chapter 4), communicative (see chapter 3), and goal-oriented (see chapter 5) functions in human-drone proxemics, the role of arousal regulation has not been adequately addressed and remains largely unexplored in the HDI literature, despite several indications of its importance. This gap is crucial to address, especially as drones, with their sound and perceived threat potential, can evoke significant arousal. Understanding how these factors influence human-drone spatial relationships is particularly important in environments with existing forms of stimulation, such as work settings or urgent situations.

6.2.2 Psychoacoustic Properties of Drone Sound

Sound Signature

Drones emit a distinct sound signature primarily generated by their rotor-based propulsion systems, distinguishing them from conventional aircraft and ground vehicles. Torija et al. [350] highlighted significant sound radiation at high frequencies in small to medium UAVs, emphasizing the unique acoustic characteristics of drone noise. Gwak et al. [159] identified this concentration of high-frequency sound energy as a defining feature of drone noise, setting it apart from other civil aircraft sounds. Additionally, Schaffer et al. [318] noted that factors such as drone model, payload, operating state, and flight maneuvers significantly influence the emission strength of drone sound, which contributes to distinct perceptual experiences compared to other noisy machines.

Perceived Loudness and Annoyance

Studies have shown that drone's sound is perceived as more annoying than conventional aircraft noise [1, 159], road traffic [85] and rail [256] noise notably due to its high-frequency broadband noise [318]. This annoyance highly depends on loudness-related metrics [242, 352]. Interestingly, such loudness varies based on the drone's model, payload, operating state, and flight maneuver. Additionally, Torija et al. [351] found that in soundscapes heavily impacted by road traffic noise, the presence of drone noise resulted in minor changes in perceived loudness, annoyance, and pleasantness. However, as Lotinga et al. [242] noted in a recent review, most studies have focused on short exposures in controlled conditions, lacking contextualized and behavioural responses and consideration of emotional connotations or personal characteristics. They argue that factors such as "sensitivity to noise" on a personal level and "the nature or importance of activities being undertaken" on a contextual level could be influential in shaping subjective responses to sound exposure, yet these aspects remain underexplored [242]. Our work directly addresses these gaps.

Research Gap

A key gap identified in existing research is the need for a deeper understanding of how personal and contextual factors influence drone noise perception. Understanding the role of these factors is crucial for advancing our knowledge of how people perceive drone sounds, particularly as drones are increasingly deployed in diverse real-world settings, involving various individuals and activities. Our study addresses this gap by exploring the interaction between drone noise perception and the cognitive load associated with tasks performed near drones, while also accounting for individual noise sensitivity.

6.2.3 Sound in Human–Drone Interactions

Theoretical Background

Psychoacoustic research highlights the significant impact that the emotional valence of sound has on perception and response. Sounds perceived as negative are generally rated as annoying and unpleasant, often triggering heightened alertness and a sense of danger, which can lead to increased physiological arousal compared to neutral sounds [25, 219, 347]. For example, Arruda et al. [25] found that sounds like crying babies and barking dogs elicited stronger sympathetic responses and impaired cognitive performance compared to neutral sounds. Additionally, higher noise levels are associated with increased annoyance and likely contribute to heightened general arousal or nervous system excitability [61], potentially leading to reduced performance, especially in tasks requiring focused attention [334]. Given that drone sounds are often perceived negatively [59], their impact on individuals could be considerable. However, this effect has not been thoroughly investigated or well understood. By measuring participants' performance under varying levels of drone noise, our study provides the first empirical insights into this issue and helps clarify the impact of drone noise exposure on cognitive performance during memory-intensive tasks.

In Human–Drone Interactions

In Human-Drone Interaction studies, participants consistently identify the sound emitted by drones as a significant source of annoyance [57, 59, 76]. This sound is often described as negative, frequently linked to the buzzing of flying insects, evoking feelings of threat and danger. Despite being frequently mentioned and recognized as a major design challenge for social drones [38], drone sound remains relatively underexplored in HDI research. Specifically, its impact on individuals is not well documented or understood, and its expected influence on the spatial relationship between people and drones remains to be thoroughly investigated. Currently, there is a limited body of literature addressing drone sound within the context of HDI. Recently, Wang et al. [370] conducted an experiment that involved overlaying natural sounds onto operating drones, revealing the potential of this approach to enhance people's perception of drone noise. However, their findings showed that this enhancement was significantly preferred only at the farthest distance (185 cm) and had no significant effect at middle (115 cm) and close distances (45 cm). The underlying reason for this remains unclear, as the study lacks a relevant theoretical explanation. Drawing on existing literature in psychoacoustics and drone noise (see section 6.2.3 and subsection 6.2.2), one possible explanation is that while natural sounds may improve the emotional valence of the experience, the negative impact of the drone's acoustic signature at closer distances may outweigh these benefits. The marked increase in perceived loudness and sharpness at closer distances supports this interpretation, but it remains uncertain whether other factors, such as the increased sense of threat due to proximity, play a role. By evaluating the impact of drone sound levels on participants' perceptions while keeping distance constant, our study offers critical insights needed for a comprehensive understanding of this phenomenon. Additionally, another HDI study found that participants in a passing situation walked closer to a robot when its sound was turned off compared to when it was on [355]. However, these results lack theoretical context and do not significantly advance the understanding of proxemic behavior. This highlights the potential importance of arousal regulation in HDI and underscores the need for dedicated studies to better understand this mechanism in human-drone interactions.

Research Gap

Drone sounds are known to elicit negative emotional responses, yet the full extent of their impact on human behavior and performance remains unclear. We address this gap by examining **how different levels of drone noise affect performance and proxemic preferences during tasks with varying mental memory loads**. While previous studies have hinted at the influence of sound on human-drone interactions, many have lacked the theoretical depth and methodological rigor needed to draw meaningful conclusions. By leveraging VR, we can precisely manipulate drone sound while controlling other variables, offering a more robust and focused understanding of how sound influences spatial behavior and cognitive performance around drones. This approach not only addresses the shortcomings of earlier research but also contributes a more theoretically grounded perspective to the field. Our research stands out by offering a strong theoretical foundation and the innovative use of virtual reality (VR) to explore the impact of drone sounds—an area that has been insufficiently investigated.

6.3 Methodology

Our study investigates how drone loudness and working memory loads interact to influence individuals' performance, subjective arousal, proxemic preferences, and sound perception. We aim to address: **1)** the shortage of observational studies on behavioral responses to drone noise, **2)** the need for deeper insights into how contextual and individual factors shape the perception and impact of drone sounds, and **3)** the role of arousal regulation in determining proxemic behavior around drones. All manipulations, measures, sample size justification, and main hypotheses were pre-registered on the Open Science Framework (OSF) before data collection: https://osf.io/hdbmn. We report all manipulations and measures in the study, in line with recent proposals [138].

As stated by Green at al. [155], analyzing the difference in noise levels needed for two noise sources to elicit equal annoyance is a valuable approach for comprehending differences in responses to different entities, and has been recently used to demonstrate the increased annoyance drones' sound generate compared to noise from other modes of transportation at comparable sound levels [85, 159, 351]. We use a similar approach in our research. In our study, participants were immersed in a mixed-reality environment (detailed in subsection 6.3.1), where they were exposed to a virtual flying drone emitting sound at three different loudness levels while performing a task with two levels of working memory load. For each condition, we collected data on performance metrics, subjective perceptions of the drone and its sound, and arousal levels. Participants were then asked to relocate themselves to a distance where they felt comfortable performing the task under those conditions, providing a proxemic measure of their preferences. This approach allowed us to assess the impact of drone loudness and working memory load on subjective sound perception, arousal, performance, and proxemics in a controlled, replicable, and valid environment.

Working Memory To manipulate working memory loads, we employed the well-established n-back task [190, 255, 257]. In our version of the task, participants were shown a series of digits between 0 and 9, presented one at a time. They were required to indicate whether each digit matched the one that appeared N steps earlier in the sequence. When N is set to 1, the task is relatively simple, requiring only a direct comparison with the immediately preceding digit. However, when N is set to 3, participants must continuously retain the last three digits in memory and compare the current digit with the one three steps prior, significantly increasing cognitive load and task difficulty. The specifics of this task are detailed in section 6.3.1.

Drone's Sound Level Real-world studies often struggle to isolate and manipulate drone sound without affecting other design elements such as size, behavior, or interaction context [370]. In contrast, VR offers a controlled environment where sound levels can be precisely adjusted while keeping other variables constant. A recent validation study demonstrates the successful application of VR systems for investigating aircraft noise perception in immersive settings [221]. Additionally, recent research has employed VR to explore the impact of drone noise on public acceptance in urban environments [340] and to examine how visual perception of drones influences responses to their noise [1]. We also integrated the latest advancements in VR technology, particularly the passthrough feature of the Meta Quest 3 headset. This feature provides high-quality rendering of the real world through its camera sensors, creating a near-augmented-reality experience. This approach enhances immersion and addresses some of the limitations inherent in traditional VR setups [176]. Further details on the experimental setup can be found in subsection 6.3.1.

6.3.1 Setup and Apparatus

This section details the experimental setup and implementations. The C# scripts, and 3D models used in this study are available on a dedicated GitHub repository and made publicly available (see [56]).

Design of Virtual Environment

The virtual environment, created with Unity 3D, overlays virtual elements onto the real experimental room as viewed through the Meta Quest 3 headset. This setup leverages the headset's passthrough feature to render the real world with added virtual components. These augmentations include virtual screens that display task-related information, instructions, and questions. Participants performed the task (see section 6.3.1) and interacted with these screens using the provided controllers, employing a laser pointer and trigger button in a manner akin to using a computer mouse. Another key augmentation is the virtual drone, a 3D model of the DJI Tello, which design is detail in section 6.3.1.

Ecological Validity Although the implementation for this study differs from previous ones, we can still apply the protocol developed in chapter 4 (see subsection 4.6.2), which aims to enhance ecological validity and facilitate the external evaluation of virtual human-drone interaction (HDI) experiments.

The value of our results extends beyond the simulation if the participants' responses to the drone's sound and task are similar to what they would experience with a real drone, and if their behavior, such as distance adjustment, mirrors what they would do in a real-world setting. The key mechanisms under investigation include arousal stimulation from sensory inputs, mental

Figure 6.1: The experimental room (left) is shown alongside the mixed-reality environment (right), which combines real-world imagery captured by the VR headset's camera sensor with additional virtual elements rendered in Unity 3D. These virtual elements include an orange circle on the ground, where participants are required to position themselves during the fixed phase of the task (see subsection 6.3.3), as well as virtual screens that display questionnaires and task-related information (such as instructions and n-nack digits)

workload associated with the task, and spatial adjustments. If the sound presented in the simulation significantly differs from that of a real drone, the results would not accurately reflect the impact a real drone might have. Therefore, creating the illusion of a real drone's presence was crucial. This was achieved by accurately replicating the drone's appearance, movement, and sound dynamics, as detailed in section 6.3.1.

Regarding the task, the n-back task's modality in the simulation closely resembles what participants would experience in the real world, as detailed in section 6.3.1. There may be some concerns about fatigue from standing and wearing the headset, which could lead to physical strain and affect mental workload [100]. To mitigate this, we allowed participants to sit during breaks and took the time to properly adjust the headset to ensure clear vision. While the potential increased fatigue from the headset's weight is a consideration, it does not undermine the validity of our results but should be acknowledged as a possible confounding factor.

In terms of proxemics, the well-known issue of distance compression in VR settings is addressed by the faithful perception of the real-world environment, with its rich spatial cues. This approach represents an optimal version of the mitigation techniques we have previously employed, such as replicating the real experimental room with accurate dimensions and visual cues.

Recent research supports the similarity between AR and real-world proxemic behaviors [176], and shows that depth perception accuracy in AR is superior to that in VR [288]. Motor abilities are likely unaffected to a significant degree. Participants are able to move freely, their proprioception remains intact as they can see their entire body—an issue that was a concern in previous work presented in chapter 5 (see section 5.4.4)—and the boundaries of their available space are consistent with those of the real room.

Overall, we consider this setting to be ecologically valid, reflecting what individuals would experience if the study were conducted in the real world.

Design of Drone

For this study, it was crucial that participants felt as though a real drone was present in the room while they performed their tasks. To achieve this, the virtual drone was designed with a focus on maximizing both visual and auditory realism, not just at a static point but dynamically as it moved.

Aspect and Behaviour The drone's visual representation utilized a 3D model of the DJI Tello, the same drone we employed in previous research. Unlike earlier approaches that relied on animations or lerp techniques for movement, this time we adopted a more sophisticated and realistic method using a PID controller [363]. This approach allowed us to replicate the drone's physical movements with high fidelity, closely matching the real DJI Tello's behavior as observed during flights, while animations were used only for the propeller rotations. A demonstration video, available on our GitHub repository [56], showcases the real DJI Tello flying alongside its virtual counterpart, highlighting their visual and behavioral resemblance.

Sound For the drone's sound, which was equally critical, we utilized a recording of an actual drone [375], pitch-adjusted to match the sound of the DJI Tello. We meticulously observed the real drone's flight, noting how its sound varied with movement and propeller speed. This sound was then programmed to mimic those subtle variations in the virtual drone. The specifics of this implementation are detailed in the C# script controlling the sound, available on the GitHub repository [56]. To manipulate the drone's loudness, we experimented with different percentages of the original recording. We created three distinct sound levels:

- Low: 5% of the original recording, categorized as a low sound level.
- Medium: 40% of the original recording, aiming to match the real drone's sound.
- High: 85% of the original recording, louder than the real drone but kept below saturation levels in the headset headphones.

While we aimed to maintain high fidelity, some sound quality was inevitably lost due to digital compression. However, the resulting sound is considered sufficiently realistic to represent what participants would experience with a real drone at varying sound levels. Additionally, the drone's sound was spatialized, ensuring that participants perceived it as originating from the virtual drone, with intensity and directionality changing according to their distance and orientation relative to it. This approach maximized the plausibility illusion, complementing the already high place illusion provided by the mixed reality setting.

Design of the N-Back Task

Description The n-back task requires participants to determine whether each stimulus in a sequence matches the one that appeared N positions earlier [198]. As N increases, the task becomes more difficult because participants must remember more elements and continuously update the remembered sequence. By adjusting N, the working memory load—and therefore the task difficulty—can be varied, with higher N levels increasing the challenge and mental workload. This makes the n-back task a useful and well-established tool for manipulating mental workload [175], although its direct connection to working memory has been questioned [198, 257]. The stimuli used in the n-back task can vary, including visuospatial items and auditory-verbal material [190]. For instance, classical n-back tasks might use numbers [246] or letters [175, 198, 257]. A sequence in the n-back task consists of a series of stimuli that include targets, non-targets, and lures, which collectively influence the difficulty of the task [198]. A target is an item that matches the stimulus presented N steps earlier in the sequence. For example, in a sequence with N = 3, such as 1-5-7-1, the final "1" is a target. A lure is an item that resembles a target but does not meet the n-back criterion; for example, in a sequence with N = 3, such as 4-5-4-3, the second "4" is a 2-back lure (or n-1 lure, where n=3 and n-1=2). Lures can increase task difficulty, particularly when they closely resemble targets. For instance, 1-back lures in a 2-back task (e.g., 7–4–5–5) often lead to more errors due to their similarity to targets, whereas 1-back lures in a 4-back task have a lesser impact [198]. A post-lure target is a target item that immediately follows a lure; for instance, in a sequence with N = 3, such as 2-5-2-2, the second "2" is a lure and the final "2" is a post-lure target. Additionally, the sequence is characterized by the duration each stimulus is visible and the interval between stimuli. Breaks of varying durations are often included between sequences to allow participants time to rest.

Task Parameters We followed similar parameters established by previous works [190, 198, 257], with one exception: we used digits instead of letters as stimuli. The stimuli consisted of pseudorandom sequences of digits (1 to 9), presented at a fixed central location on a virtual screen positioned 0.85 meters from the participants (see Figure 6.2). Each digit was displayed for 500 milliseconds, followed by a 2000-millisecond interstimulus interval.

For each digit presented, participants were required to respond to both target and non-target

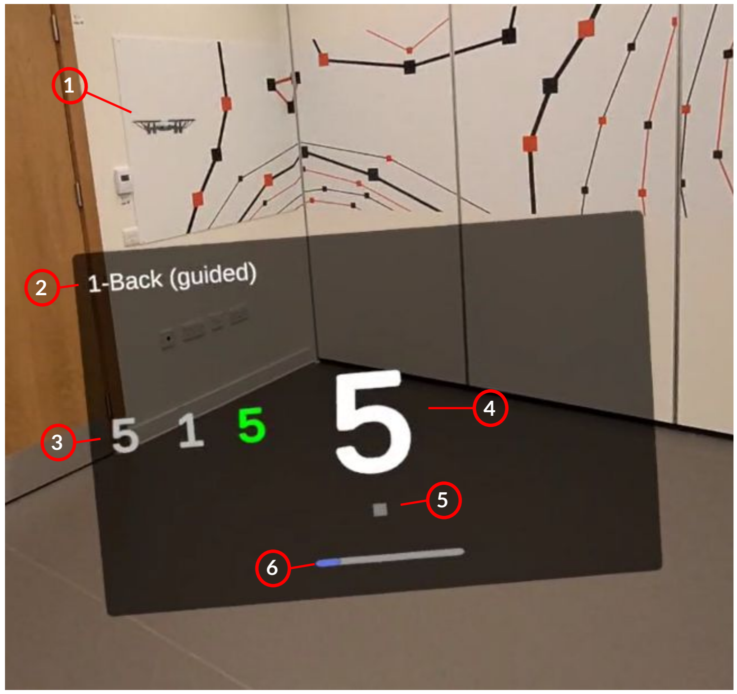


Figure 6.2: **(1)** In the background, a virtual drone faces the participants, moving erratically along a horizontal line. This drone, which serves as the source of the spatialized sound, emits noise that changes based on its movements and the participants' relative position (distance and orientation), simulating the perception of a real drone's noise. **(2)** The screen that participants face displays the current n-back task condition, either "1-back" or "3-back," with a "guided" label if the task is in the guided training version, as explained later. **(3)** During the training session, the "guided" version shows the three most recently displayed digits on the screen. The digit relevant to the current task is highlighted in green if it matches the displayed digit, or red if it does not. These digits are not visible during the actual task. **(4)** Each digit in the series is displayed in the center of the screen for 0.5 seconds. **(5)** If no response is provided (i.e., no button is pressed on the controllers), the square below the digit remains grey. During the training session, the square turns green for a correct response and red for an incorrect one. In the actual task, the square turns white after a response to indicate that it has been registered, but participants are not informed if their response was correct. **(6)** Participants have 2.5 seconds from the appearance of each digit to provide their response, with the time limit visually represented by a filling line at the bottom of the virtual screen. When the 2.5 seconds elapse, the square below the digit returns to grey, and a new digit is displayed. If a participant does not respond within this time frame, it is recorded as an omission and added to the total error count.

stimuli, as previously done in [198, 257]. They indicated whether the current stimulus matched the one presented N steps earlier by pressing the right controller's trigger button for a match (target) and the left controller for a mismatch (non-target). Errors, including omissions, false positives, and false negatives, were recorded and used to calculate participants' accuracy (see subsection 6.3.2).

Before starting the actual task, participants completed training on both task difficulty conditions. They were given two practice blocks (each consisting of 25 trials) per condition, with feedback provided on their performance. One of these practice blocks included a guided version, as detailed in Figure 6.2. Participants then completed six blocks (in a 2x3 within-subject design) of 25 responses each (26 digits for the 1-back task and 28 for the 3-back task) in a randomized order using a Latin square design. Each block contained 30% target items, along with some n-1 and n-2 lures, although we did not control for these, potentially leading to variations in difficulty between sequences. As commonly observed in studies using n-back tasks, Reaction times (RTs) and accuracy measures were obtained for the other blocks (see subsection 6.3.2) [255]. After each block, participants completed a set of questions (see subsection 6.3.2). They also performed an additional block of 15 digits under the same conditions, during which they were instructed to find the minimum comfortable distance for performing the task while being exposed to the drone's sound. Throughout the study, participants were initially positioned 2.45 meters from the virtual flying drone, a distance corresponding to the middle of Hall's social space (1-4 meters). During the distancing phase, this positioning allowed participants to either approach or move away from the drone, potentially shifting into different proxemic spaces (personal or public) as defined by Hall's framework [163]. This specific starting distance was selected to enable participants to explore various levels of comfort in relation to the drone and make full use of the room's dimensions. During this phase, participants could choose to stay in their initial position or move within the room, either approaching or distancing themselves from the drone along a designated line. The virtual screen moved with them, maintaining a constant distance to ensure it did not influence their choice of distance. Performance data were not collected for this distancing block. After the distancing phase, participants were given a 1-minute break, during which they could sit on a chair to rest. They were then required to return to the orange circle on the ground (see Figure 6.1, indicating where they should stand while performing the task. When ready to continue, participants clicked "start" on the virtual screen to proceed with the next set of conditions.

To confirm that the task conditions (1-back and 3-back) induced different levels of mental workload, we compared performance outcomes and NASA-TLX scores as a manipulation check.

6.3.2 Study Design

The study employs a 2x3 within-subject design with two independent variables: "Drone Sound Level" (3 levels characterized by varying percentages of the original drone sound, labeled as Low (5%), Medium (40%), and High (85%)) and "Working Memory Load" (2 levels characterised by the value of the N parameter of the n-back task and labelled as: Low - N=1 and High - N=3). The order of the experimental conditions is randomized using a Latin square design. After having performed the n-back task at a fixed position from the drone for 25 digits under a given sound level and working memory load condition, participants answer a set of likert type questions described below providing a subjective evaluation of their arousal, perception of the drone's sound, awareness of the drone and mental workload (Nasa-TLX). They then continued the task under the same conditions, with instructions to move to the minimum distance at which they felt comfortable. Participants could experiment with different distances before starting and could adjust their position throughout the task (15 digits) if they felt the need to try different locations. The final position they chose served as the proxemic indicator of their preferred distance for analysis.

Sound Perception To assess participants' perceptions of the drone's sound, we collected subjective measures of perceived loudness (PL) and perceived annoyance (PA), both of which are commonly used in psychoacoustic studies, particularly those focused on drone sound perception [159, 242, 370]. Given that some participants in our previous studies described the drone sound as threatening, and that we found perceived threat (PT) to be correlated with subjective stress and preferred distances [59], we also measured the subjective threat level associated with the sound. After each condition, participants rated these three aspects using the following 10-point Likert scales:

- (PL) **How loud did you perceive the sound of the drone to be?** *(0 - Not Loud At All, 1-3 - Slightly Loud, 4-6 - Moderately Loud, 7-8 - Very Loud, 9-10 - Extremely Loud)*
- (PA) **Rate your level of annoyance caused by the sound of the drone.** *(0 - Not Annoyed At All, 1-3 - Slightly Annoyed, 4-6 - Moderately Annoyed, 7-8 - Very Annoyed, 9-10 - Extremely Annoyed)*
- (PT) **How threatening did you perceive the sound of the drone to be?** *(0 - Not Threatening At All, 1-3 - Slightly Threatening, 4-6 - Moderately Threatening, 7-8 - Very Threatening, 9-10 - Extremely Threatening)*

These measures allowed us to evaluate how varying drone sound levels, task-related cognitive load, and their interaction influenced individuals' perceptions of the drone's sound. Additionally, they enabled us to analyze the relationships between these subjective perceptions and other metrics detailed below, including proxemic adjustments.

Subjective Arousal Previous research suggests that physiological arousal during an event is linked to self-assessments of the physical reactions it elicits [308]. Building on this, we used a similar Likert scale and asked participants:

- (Arousal) **Rate the intensity of your physical reaction (bodily reaction) to what you've just experienced. On a scale from 0 (minimum) to 10 (maximum)**.

This offered a subjective evaluation of the intensity of their physical response to the experience. It allowed us to assess how varying drone sound levels, task-related cognitive load, and their interaction influenced individuals' subjective arousal and its relationship with other metrics, including proxemic adjustments.

Drone's Presence In addition to assessing participants' perception of the drone's sound, we also evaluated their overall awareness and discomfort related to the drone's presence. Participants were asked the following questions:

- (Awareness) **How aware were you of the drone's presence?** *(0 - Not Aware At All, 1-3 - Slightly Aware, 4-6 - Moderately Aware, 7-8 - Very Aware, 9-10 - Extremely Aware)*
- (Bother) **How much did the drone's presence bother you?** *(0 - Not Bothered At All, 1-3 - Slightly Bothered, 4-6 - Moderately Bothered, 7-8 - Very Bothered, 9-10 - Extremely Bothered)*

Nasa Task Load Index The NASA-TLX is a widely recognized multi-dimensional scale used to measure perceived workload during or immediately after task performance [166]. In our study, participants completed the NASA-TLX after each block of 25 digits, enabling us to confirm workload differences between the 1-back and 3-back tasks and assess the impact of drone sound exposure on these perceived workloads.

Performance We evaluated participants' performance on the n-back task following recent recommendations for reporting and interpreting working memory performance in such tasks [255]. Consistent with common practices [255,257], we used Reaction Time (RT) and Accuracy (in %) as the primary performance indicators. During the task, participants had 2.5 seconds to indicate whether the displayed digit matched the one presented N positions earlier by pressing the right controller if there was a match and the left controller if there was not.

- **Reaction Time (RT)** was measured as the time elapsed (in seconds) between the presentation of a digit and the participant's response, which was constrained to a window of 0 to 2.5 seconds.
- **Accuracy** was calculated as the percentage of correct responses using the following formula:

$$Accuracy = (1 - (Errors/25)) * 100 = (Correct/25) * 100 \quad (1)$$

  Errors were calculated as the sum of False Negatives (pressing the left button when there was a match), False Positives (pressing the right button when there was no match), and Omissions (failing to respond within the time window). **Correct responses** were categorized as True Positives (pressing the right button when there was a match) and True Negatives (pressing the left button when there was no match).

Similar to the NASA-TLX, these measures were used to verify the expected performance differences between the 1-back and 3-back tasks, while also assessing the impact of drone sound exposure on task performance.

Proxemics We calculated the minimum comfortable distance (in meters) by recording the final position chosen by participants to perform the task while exposed to the drone's sound and presence. This measure reflects spatial adjustments that may occur in response to drone-related stimuli and the influence of the working memory load associated with the task. Asking participants to select this minimum distance helps identify a threshold, although it was constrained by the room's dimensions and potentially influenced by the initial fixed distance. As participants moved closer to or farther from the drone, the screen displaying the digits moved with them so that it doens't impact their ability to perform the task. Additionally, we implemented spatialized sound, so the drone's noise adjusted—decreasing as they moved away and increasing as they approached.

Questionnaires Each questionnaire used in this study was designed to assess potential confounding factors or to support quantitative results. The questionnaires were created in FormR and completed by participants on the experimenter's computer upon arrival, immediately after they provided consent. Responses were recorded using a unique subject ID to ensure the data remained anonymous and dissociated from personal identities. Before the experiment began, participants filled out a **demographic questionnaire** that collected information on their *age*, *gender*, and *prior experience with drones*. Additionally, participants completed the abbreviated version of the **Noise Sensitivity Scale** (NSS) [41] to gauge their sensitivity to sounds, as individual differences in noise sensitivity could introduce variability in the results. They also answered an adapted version of the Negative Attitude Towards Robots Scale (NARS) [267, 268], where the term "robot" was replaced with "drone," to assess their prior attitudes towards drones. After the experiment, participants rated the realism of the drone sound, following procedures used in previous studies that investigated sounds in VR [221]. The study concluded with a brief (10-minute) semi-structured interview designed to complement the questionnaire data and provide deeper insights into participants' experiences. During the interview, participants were asked to explain their reasons for selecting a particular distance, the impact of the drone's sound on them, perceived differences between the sound levels, and how the task's difficulty influenced their perception of the sound and its effects.

6.3.3 Protocol

At the agreed date and time, participants are welcomed at the entrance of the experimental building. They are guided to the experimental room and asked to fill in a consent form and complete pre-study questionnaires, including demographics, a short version of the Noise Sensitivity Scale (NSS), and an adapted version of the Negative Attitude Towards Robots Scale for drones. They are then provided with documents detailing their role in the study and the task they will perform. Participants are invited to ask questions, and the experimenter verbally reiterates the explanations to ensure clarity.

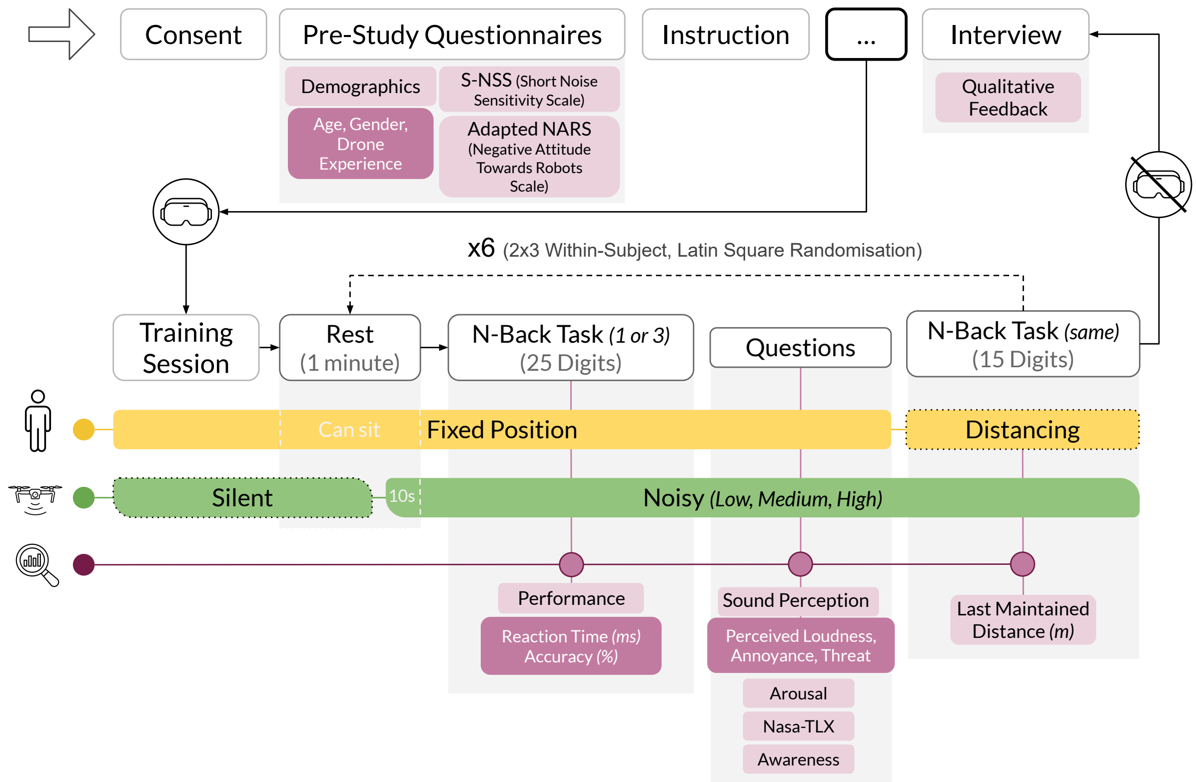


Figure 6.3: Overview of the Experiment Protocol

Next, participants are invited to wear the VR headset, immersing them in a mixed-reality environment where they can see the real world with a few added virtual elements (see Figure 5). Standing at a specific point in the middle of the room, they begin a training session to familiarize themselves with the n-back task under its two conditions. The training session consists of two blocks of 25 digits for each condition. Participants receive feedback on the correctness of their responses, and in the first block of each condition, the last three displayed digits remain visible to assist them.

The training session is followed by a one-minute resting period, which occurs after each set of conditions. During the rest, a screen instructs participants to check the left screen for the next n-back condition and to return to the marked location after 60 seconds. To mitigate the sudden impact of the drone's sound, it gradually increases to its target level 10 seconds before the end of the resting period. After the one-minute rest, participants start the task at their convenience by clicking "start" on the screen displaying the digits.

After 25 stimuli, the task pauses, and participants answer a set of questions on a virtual screen to their right. New instructions then explain that they can continue the task with the goal of finding the threshold distance at which they consider the drone's sound and presence acceptable for performing the task. They click "Continue" to proceed with an additional 15 stimuli, during which they can adjust their distance from the drone.

Once this block is completed, participants rest for one minute, and the same protocol is repeated from the last resting phase. After experiencing each set of conditions, a pop-up message indicates that they can remove the headset. The study concludes with a five-minute interview to collect their thoughts on the experience. The entire study lasts 50 minutes, and participants are thanked at the end, receiving a £10 Amazon voucher as compensation.

6.3.4 Participants

We recruited 30 participants, consisting of 11 males and 19 females. This sample size adheres to the standards established within the HCI field for within-subject designs [70] and is comparable to, or larger than, the sample sizes used in previous studies on human-drone proxemics, some of which employed similar or smaller sample sizes [107, 389]. The participants were of diverse ages, ranging from 19 to 54 years, with a mean age of 26.43 years, indicating generally good and comparable motor abilities. Participants were also asked to identify the region or regions they associate with their primary cultural background, allowing for multiple selections. The responses were distributed as follows: Europe (13), Asia Pacific (15), Middle East (1), Africa (1).

Regarding prior experience with drones, 2 participants reported never having seen a drone ("No experience"), 24 had seen a drone ("Little Experience"), and 4 had used drones ("Quite a bit of Experience"). Alongside demographic information, we assessed participants' prior negative perceptions of drones using an adapted version of the Negative Attitude Towards Robots Scale [267, 268] and their sensitivity to noise using the Noise Sensitivity Scale - Short Form (NSS-SF [41]) (see subsection 6.3.2). A summary of the demographic data is provided in Table 6.1.

In the results section, we report the statistical tests conducted to evaluate the influence of these pre-assessed potential confounding factors on proxemic behaviors. Recruitment was conducted through the university's mailing list and word of mouth. All participants provided informed consent before participating in the study. The research received ethical approval from the University of Glasgow Ethics Committee (reference number: 300230169).

6.4 Results

This section presents a comprehensive analysis of the collected data, including both descriptive statistics and the outcomes of statistical tests conducted to evaluate significant differences and relationships. We begin with a Manipulation Check section, where we verify the effectiveness of our two key variables: drone sound level and working memory load. Following this, we assess the potential impact of individual characteristics, specifically examining how individual differences in noise sensitivity and negative attitudes toward drones might influence the results. This analysis helps to deepen our understanding of the role of personal characteristics in the perception of drone sounds. The main analysis investigates the effects of varying drone sound

Table 6.1: Demographics Summary

Number of Participants		30
Gender	Male	11
	Female	19
Age	M	26.43
	SD	7.4
	Range	19-54
Cultural Background (Top 5)	India	7
	United Kingdom	7
	China	4
	Europe (Italy+Germany)	4
	Thailand	2
Drones' Experience	None	2
	A Little	24
	Quite a Bit	4
	A Lot	0
NARS [M,SD]	NARS	[-0.18,0.6]
Subscales	Interaction	[-0.4,0.75]
	Social	[0.03,0.74]
	Emotion	[-0.1,0.96]
NSS-SF [M,SD]	NSS	[3.88,1.05]

levels and working memory load across several metrics. These are categorized into **Sound Perception** (including perceived annoyance, loudness, and threat), **Drone Presence** (awareness and bother), **Subjective Arousal and Maintained Distance** (to explore the role of proxemic behaviors in arousal regulation), **Performance Metrics** (reaction time and accuracy), and the **NASA-TLX** (to assess subjective task performance experience under different conditions). To enhance reader navigation through this results section, we have provided visual indicators and summaries as follows:

Green boxes outline the results of manipulation checks.

Blue boxes summarize the analysis of potential confounding variables related to individual characteristics measured prior to the study.

Orange boxes highlight the key findings of the main analysis.

6.4.1 Manipulation Check

Drone Sound Levels

In this study, we aimed to establish three distinct drone sound levels: low, medium, and high. Detailed information about their implementation can be found in subsection 6.3.1. To verify the effectiveness of this manipulation, we aggregated and averaged participants' perceived loudness ratings for each sound level across the two task conditions. Perceived loudness was assessed using a Likert scale from 0 (Not loud at all) to 10 (Extremely loud) (see Methodology section 5.3). Fisher's ANOVA (One-Way ANOVA) was used to determine if there were significant differences between the mean ratings for the three sound levels.

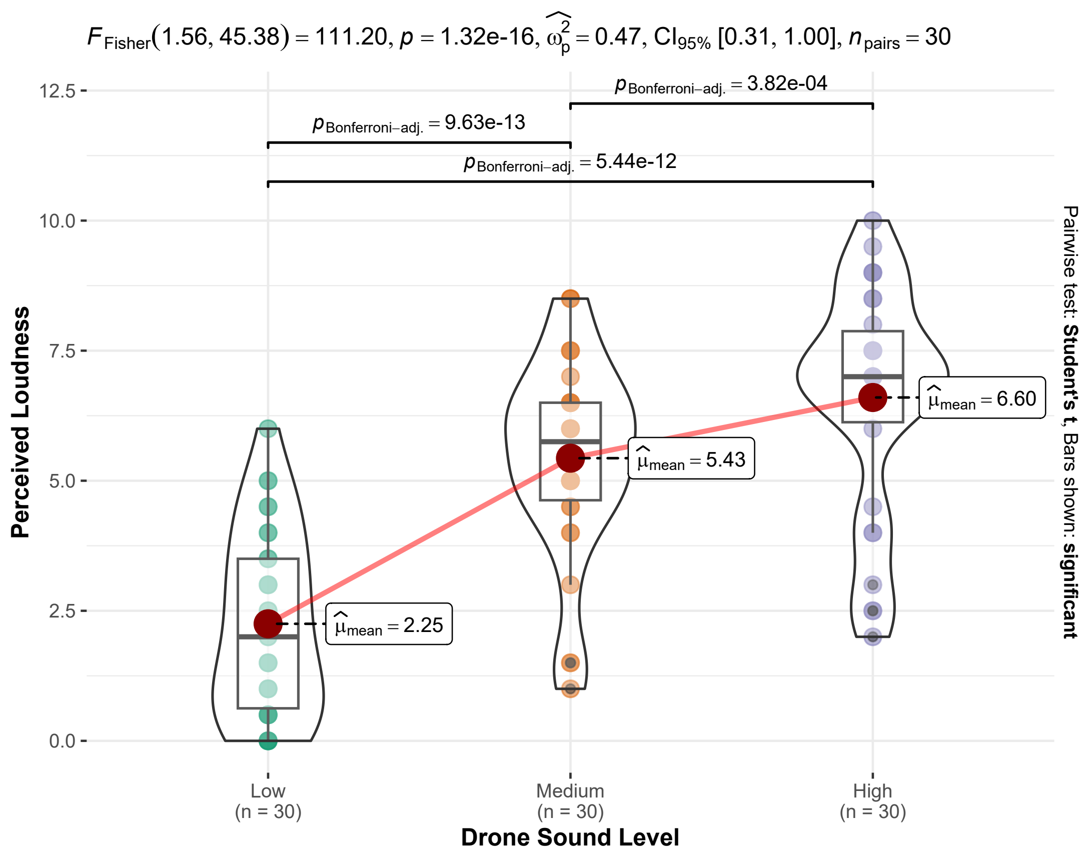


Figure 6.4: Boxplot and violin plots illustrating participants' perceived loudness for the three drone sound level conditions. The plots demonstrate the effective manipulation of sound levels, with the means aligning with the expected categories: "Slightly Loud" for the Low sound level, "Moderately Loud" for the Medium sound level, and between "Moderately Loud" and close to "Very Loud" for the High sound level. Significant differences between each condition have been verified, and a large effect size suggest that the sound levels account for a substantial proportion of the variance in perceived loudness.

We verified that the data met the ANOVA assumptions: independence of observations was confirmed, normality was tested using the Shapiro-Wilk test (Low: p=0.0705, Medium: p=0.0767, High: p=0.0190), showing normal distribution for Low and Medium levels but not for High, and homogeneity of variances was assessed with Levene's test (p=0.9183). The ANOVA results revealed a significant effect of sound levels on perceived loudness ($F(1.56, 45.38) = 111.20, p = 1.32e-16, \omega_P^2 = 0.47$). Partial omega squared (ω_P^2) [217,275] was calculated to assess the effect size, yielding a value of 0.47. This indicates a large effect size, suggesting that the sound levels account for a substantial proportion of the variance in perceived loudness. Bonferroni-corrected post-hoc pairwise comparisons indicated significant differences between all sound levels. The mean perceived loudness scores were 2.25 (SD=1.76, min=0, max=6) for the Low sound level, corresponding to "Slightly Loud" (1-3); 5.43 (SD=1.90, min=1, max=8.5) for the Medium sound level, corresponding to "Moderately Loud" (4-6); and 6.60 (SD=2.17, min=2, max=10) for the High sound level, which lies between "Moderately Loud" and "Very Loud" (7-8) (see Figure Figure 6.4).

Cognitive Load

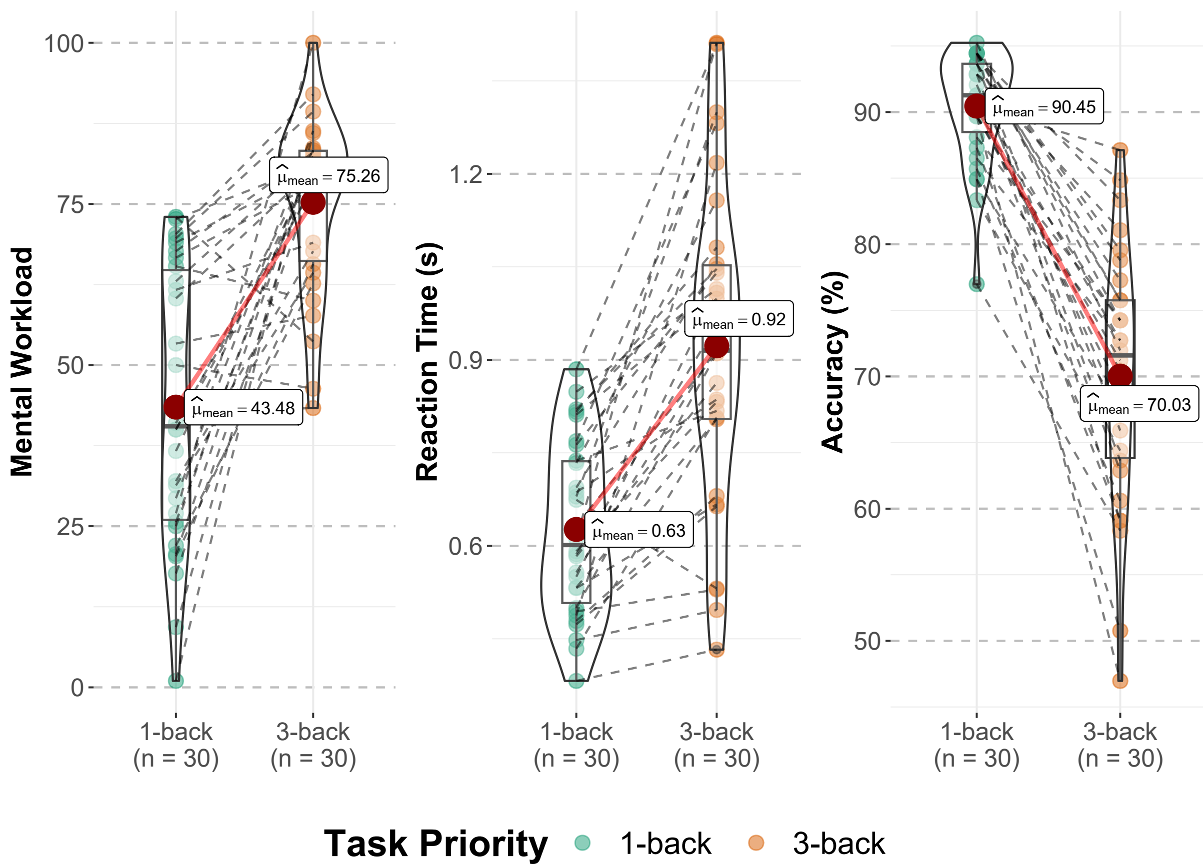


Figure 6.5: Boxplot and violin plots showing participants' subjective mental workload (as reported in the NASA TLX), reaction time (in seconds), and response accuracy (in %) averaged across each task condition. From left to right, the plots illustrate these metrics for the 1-back and 3-back conditions. The results demonstrate effective manipulation of cognitive load, with significantly higher mental workload, longer reaction times, and lower accuracy observed for the more challenging 3-back condition compared to the 1-back condition.

To manipulate participant mental workload and examine its interaction with varying drone sound levels on aspects such as sound perception, drone perception, performance, subjective arousal, and proxemic preferences, we utilized the well-established n-back task. Specifically, we employed the 1-back and 3-back versions to induce two distinct levels of mental workload, categorized as low and high. Details on the task implementation can be found in the Setup and Apparatus section (subsection 6.3.1).

To evaluate the effectiveness of this manipulation, we aggregated and averaged participants' mental workload ratings from the NASA Task Load Index, along with performance metrics such as reaction time and accuracy for each n-back task across the three sound level conditions. Student's t-tests revealed significant effects of the task condition on perceived mental workload (t(29) = -6.55, p = 3.53e-07, g_{Hedges} = -1.17), reaction time (t(29) = -7.79, p = 1.37e-08, g_{Hedges} = -1.38), and accuracy (t(29) = 13.36, p = 6.39e-14, g_{Hedges} = 2.28). The calculated Hedges' g, which exceeded 0.75 in each case, indicates large effect sizes [63], suggesting that the task conditions account for a substantial proportion of the variance in perceived mental workload, reaction time, and accuracy. As illustrated in Figure 6.5, the 3-back task induced significantly higher mental workload (M_{3-back} = 0.92s vs. M_{1-back} = 0.63s), longer reaction times (M_{3-back} = 75.26s vs. M_{1-back} = 43.48s), and lower accuracy (M_{3-back} = 70.03% vs. M_{1-back} = 90.45%).

These findings confirm the successful manipulation of mental workload through the two n-back task levels, as evidenced by both subjective ratings and objective behavioral measures.

Validation of Independent Variables

- **Drone sound levels –** Labeled as *Low*, *Medium*, and *High*, the drone sound levels detailed in subsection 6.3.1 were distinctly and accurately perceived by participants, as indicated by the mean perceived loudness and significant differences between each group. These results confirm the effectiveness of our manipulation in creating distinct drone sound levels, ensuring that participants experienced varying levels of sound exposure.

- **Task Cognitive Load –** Our manipulation of participants' mental workload using the well-established n-back task at two difficulty levels (1-back and 3-back) was successful. The 3-back task led to a significant increase in perceived mental workload, longer reaction times, and lower accuracy compared to the 1-back task. This confirms the effectiveness of our manipulation in creating two distinct scenarios with significantly different levels of cognitive load.

6.4.2 Individual Characteristics

Before delving into the primary analysis, we conducted an evaluation of potential confounding variables related to individual characteristics, which were measured prior to the study, including noise sensitivity, and negative attitude towards drones. The groups defined by categories of prior experience with drones were too unbalanced to conduct meaningful statistical tests (see Table 6.1).

To investigate the relationship between participants' noise sensitivity and negative attitude towards drones (as measured by the NSS-SF and an adapted NARS), and their perception of the drone (Awareness, Bother) and its sound (Perceived Annoyance, Loudness, Threat), proxemic preferences (distance), subjective arousal, performance (RT, Accuracy), and mental workload (NASA-TLX), we conducted Spearman's Rank Correlation tests for each condition separately. Spearman's correlation was chosen because it is well-suited for ordinal data, such as Likert scales, and is effective in assessing monotonic relationships. Unlike Pearson's correlation, Spearman's does not assume linearity or a normal distribution, making it a more flexible tool for analyzing data that may not meet these assumptions. Given the potential variability in how different conditions might influence the relationship between noise sensitivity and other variables, we opted for a multi-level approach to analysis, ranging from condition-specific to general analyses. This approach minimizes the risk of overgeneralization and provides a more nuanced understanding of these relationships.

- **Level 0** involves verifying correlations for each specific set of conditions (e.g., combinations of task difficulty and sound level).
- **Level 1** assesses correlations within each condition independently (e.g., across all participants within a single task or sound level).
- **Level 2** examines correlations across the entire dataset.

This comprehensive approach is intended to enhance our understanding and interpretation of these relationships, ensuring that no important patterns are overlooked. To avoid violating the independence assumption between samples, we aggregated and averaged measurements across conditions. This aggregation ensures that each participant contributes only one data point per condition level (e.g., one noise sensitivity measure paired with one perceived annoyance measure), rather than multiple data points from repeated measures. This adjustment allows for proper paired observations when performing the correlation tests. The significant correlations observed are reported below in Tables, with p representing the p-value and r_s the Spearman correlation coefficient, which ranges from -1 to 1. The closer r_s is to these extremities, the stronger the relationship. While there is no universally accepted standard for categorizing r_s [13, 314], we follow the guidelines recommended for Pearson correlations by Schober et al. (2018) [314].

According to these guidelines, correlations are categorized as follows: insignificant if $r_s < 0.1$, weak if $r_s < 0.39$, moderate if $r_s < 0.69$, strong if $r_s < 0.89$, and very strong if $r_s > 0.9$.

Noise Sensitivity

The NSS scores for the sample (N = 30) were analyzed to assess central tendency, variability, and distribution. The scale ranges from 1, indicating low sensitivity, to 6, indicating high sensitivity to noise. In our sample, the mean NSS score was 3.88 (SD = 1.05), with individual scores ranging from 1.20 to 5.8. This distribution suggests that the overall noise sensitivity among participants was generally moderate, with some individuals displaying very low or very high sensitivity. The Shapiro-Wilk test indicated that the NSS scores were approximately normally distributed (W = 0.976, p = 0.712). The internal consistency of the NSS was high, with a Cronbach's alpha of 0.89, suggesting good reliability for the scale in this sample [348]. A Spearman correlation test revealed a weak and statistically non-significant relationship between NSS and negative attitude towards drones (adapted NARS) ($r_s = 0.31$, p = 0.093). This result suggests that noise sensitivity and negative attitudes towards drones are likely independent of each other in this sample.

Sound Perception Noise sensitivity was correlated with perceived annoyance and loudness under specific conditions (see Table 6.2), but no correlation was found with perceived threat.

Table 6.2: **Spearman's Rank Correlation tests results between noise sensitivity and sound perception metrics, specifically Perceived Annoyance and Perceived Loudness.** Only significant correlations are shown, except for Level 2 tests.

		Condition		p.value (sign.)	Strength
Perceived Annoyance	**Level 0**	Medium	3-Back	0.0042 (**)	0.51 (Moderate)
	Level 1 N-Back		3-Back	0.011 (**)	0.46 (Moderate)
	Level 1 Sound Level		Medium	0.047 (*)	0.37 (Weak)
	Level 2			0.08 (ns)	0.32 (Weak)
Perceived Loudness	**Level 0**	Medium	3-Back	0.00016 (***)	0.63 (Moderate)
	Level 1 N-Back		3-Back	0.01 (**)	0.46 (Moderate)
	Level 1 Sound Level		Medium	0.042 (*)	0.37 (Weak)
	Level 2			0.098 (ns)	0.31 (Weak)

- **Perceived Annoyance** The results are presented in Table 6.2. The strength of the correlation between noise sensitivity and perceived annoyance decreases as the level of analysis broadens. At Level 0, the correlation is moderate (0.51), indicating a notable relationship specifically under the medium sound level during the 3-back task. At Level 1, the correlation remains moderate when focusing on the the 3-back task alone (0.46) and becomes weak for the medium sound level condition (0.37). However, at Level 2, where data from all conditions are combined, the correlation becomes insignificant. While the relationship between noise sensitivity and perceived annoyance is relatively strong under specific conditions, it diminishes when broader conditions are considered. This pattern suggests that the impact of noise sensitivity on perceived annoyance is influenced by the specific context, with certain conditions amplifying this relationship more than others.

- **Perceived Loudness** The results are presented in Table 6.2. The relationship between noise sensitivity and perceived loudness is strongest at the condition-specific level (Level 0) and remains moderately strong when analyzed by task condition (Level 1). However, this relationship becomes weaker and statistically non-significant at the aggregated level (Level 2), indicating that as for perceived annoyance the specific conditions may influence the perception of loudness in relation to noise sensitivity.

Drone Presence Noise sensitivity was correlated with participants' awareness of the drone in specific conditions and with how bothersome they found its presence across several conditions (see Table 6.2).

Table 6.3: **Spearman's Rank Correlation tests results between noise sensitivity and drone's presence metrics of awareness of degree of bother.** Only significant correlations are shown, except for Level 2 tests.

		Condition		p.value (sign.)	Strength
Awareness	**Level 0**	Medium	3-Back	0.0029 (**)	0.53 (Moderate)
	Level 1 N-Back		3-Back	0.0094 (**)	0.47 (Moderate)
	Level 1 Sound Level		Medium	0.015 (*)	0.44 (Weak)
	Level 2			0.084 (ns)	0.32 (Weak)
Bother	**Level 0**	Medium	1-Back	0.0089 (**)	0.47 (Moderate)
		Medium	3-Back	0.015 (*)	0.44 (Moderate)
		Low	3-Back	0.02 (*)	0.42 (Moderate)
	Level 1 N-Back		1-Back	0.014 (*)	0.44 (Moderate)
			3-Back	0.0063 (**)	0.49 (Moderate)
	Level 1 Sound Level		Low	0.039 (*)	0.38 (Weak)
			Medium	0.0057 (**)	0.49 (Moderate)
	Level 2			0.0082 (**)	0.47 (Moderate)

- **Awareness** The results are presented in Table 6.3. The relationship between noise sensitivity and awareness of the drone is most robust under specific conditions (Level 0), particularly during the Medium sound level and 3-back task. As the analysis broadens to consider sound levels and task conditions independently (Level 1), the correlation remains moderate but weakens slightly. This trend continues at Level 2, where the correlation weakens further and is no longer statistically significant. These findings, along with previous results, suggest that the influence of noise sensitivity becomes significant in specific contexts, highlighting the importance of situational factors.

- **Bother** The results are presented in Table 6.3. Unlike the previous variables, the relationship between noise sensitivity and how bothered participants were by the drone's presence remains significant across all levels of analysis. Although the correlation strength varies from weak to moderate across different conditions (Level 0 and Level 1), the consistency of significant results suggests a general effect of noise sensitivity on how bothered participants feel, with some conditions exacerbating this effect.

Performance Noise sensitivity was correlated with participants' reaction time across several conditions but not with their response accuracy (see Table 6.4).

Table 6.4: **Spearman's Rank Correlation tests results between noise sensitivity and reaction time.**

		Condition		p.value (sign.)	Strength
Reaction Time	**Level 0**	Low	1-Back	0.0011 (***)	-0.57 (Moderate)
		Medium	1-Back	0.00034 (***)	-0.61 (Moderate)
		High	1-Back	0.00024 (**)	-0.62 (Moderate)
		Low	3-Back	0.0061 (***)	-0.49 (Moderate)
		Medium	3-Back	0.0035 (**)	-0.52 (Moderate)
		High	3-Back	0.0071 (**)	-0.48 (Moderate)
	Level 1 N-Back		1-Back	6.6e-05 (***)	-0.66 (Moderate)
			3-Back	0.0024 (***)	-0.53 (Moderate)
	Level 1 Sound Level		Low	0.0014 (***)	-0.56 (Moderate)
			Medium	1.9e-05 (***)	-0.7 (Strong)
			High	8.9e-05 (*)	-0.65 (Moderate)
	Level 2			5.7e-05 (***)	-0.67 (Moderate)

- **Reaction Time** The results are presented in Table 6.4. The strength of the negative correlation between noise sensitivity and reaction time is robust across all levels of analysis. This consistent negative correlation underscores the influence of noise sensitivity on task performance, where higher sensitivity leads to slower reaction times across different contexts.

Non-Significant Results For the other variables (accuracy, perceived threat, maintained distance, and NASA-TLX subscales such as mental workload, physical workload, pressure, perceived performance, frustration, and effort), no significant correlations with noise sensitivity were observed across any level of analysis. This lack of significant results suggests that noise sensitivity may not have a meaningful impact on these specific outcomes, or that the sample size and variability within the conditions were insufficient to detect such effects. The only exception was a weak negative correlation between noise sensitivity and perceived performance at the High sound level (r_s= -0.38, p=0.037), which was isolated to this specific condition.

Summary - Noise Sensitivity

- **Key Findings:** Our results reveal a positive monotonic relationship between noise sensitivity and the perception of the drone's sound, especially in terms of loudness and annoyance, under moderate sound levels during the 3-back task. Additionally, a significant positive correlation was observed between noise sensitivity and drone awareness in these conditions. A broader correlation was also found between noise sensitivity and how bothered participants were by the drone's presence across various conditions. Lastly, higher noise sensitivity was consistently associated with slower reaction times across all conditions.

- **Interpretation:** Section 6.5.3 discusses potential explanations for these findings, suggesting that they may be influenced by a combination of cognitive resource allocation during the task and the intensity of the drone's sound, which could hinder participants' ability to maintain focus.

- **Limitations:** Methodological limitations, particularly regarding our measurement approach, are also discussed in the same section, underscoring the need for more refined techniques to capture subtle differences in sound perception.

Negative Attitude Towards Drones

The adapted NARS scores, modified from the Negative Attitude Towards Robots Scale by substituting "robot" with "drone," were analyzed to evaluate their central tendency, variability, and distribution. The scale ranges from -2, indicating a non-negative attitude, to 0, indicating a neutral attitude, and up to 2, indicating a negative attitude towards drones. In our sample, the mean NARS score was -0.12 (SD = 1.05), with individual scores ranging from -1.22 to 0.8. This distribution suggests that the overall attitude towards drones among participants was relatively neutral. The Shapiro-Wilk test confirmed that the NARNS scores were approximately normally distributed (W = 0.965, p = 0.411). The internal consistency of the NARNS was acceptable, with a Cronbach's alpha of 0.76, indicating satisfactory reliability for the scale in this sample.

As noted previously, the results of the Spearman's Rank Correlation test between NARNS and NSS indicated a weak and statistically non-significant relationship, suggesting the absence of a meaningful association between negative attitudes towards drones and noise sensitivity.

The significant relationships between negative attitudes toward drones and our variables of interest, as determined by Spearman's Rank Correlation tests, are detailed in Table 6.5.

Table 6.5: **Spearman's Rank Correlation tests results between negative attitude towards drones and our independent variables.** Only significant correlations are shown.

		Condition		p.value (sign.)	Strength
Perceived Annoyance	**Level 0**	Medium	3-Back	0.0016 (**)	0.43 (Moderate)
	Level 1 Sound Level		Medium	0.029 (*)	0.4 (Moderate)
Perceived Loudness	**Level 0**	Medium	1-Back	0.047 (*)	0.37 (Weak)
Perceived Threat	**Level 1** Sound Level		Medium	0.048 (*)	0.36 (Weak)
Subjective Arousal	**Level 0**	Medium	1-Back	0.036 (*)	0.36 (Weak)
NASA-TLX Frustration	**Level 0**	High	1-Back	0.014 (*)	0.38 (Weak)
Reaction Time	**Level 0**	Low	1-Back	0.032 (*)	-0.39 (Weak)
	Level 1 Sound Level		Medium	0.028 (*)	-0.4 (Moderate)
			High	0.0016 (**)	-0.44 (Moderate)
	Level 1 N-Back		1-Back	0.048 (*)	-0.36 (Weak)
			3-Back	0.049 (***)	-0.36 (Weak)
	Level 2			0.023 (*)	-0.41 (Moderate)

Non-Significant Results In contrast to the significant relationships observed in Table 6.5, no significant correlations were found between NARS and several other variables, including awareness of the drone, how bothered participants were by the drone's presence, accuracy, maintained distance, mental workload, physical workload, pressure, perceived performance, and effort. This suggests that the influence of NARS on these aspects is either weak or nonexistent in the current sample and context.

Summary - Negative Attitude Towards Drone Our results show that a negative attitude toward drones was positively correlated with perceived annoyance, loudness, threat, subjective arousal, and frustration under specific conditions, and negatively correlated with reaction time across multiple conditions (see Table 6.5). However, overall, these metrics appear to have a limited and context-dependent impact on how participants perceived and responded to the drone. The lack of strong and consistent effects across different measures suggests that negative attitudes toward drones are not a major factor influencing the outcomes studied here. As a result, these findings offer limited practical implications or theoretical advancements. The relationship with reaction time is further discussed in Section 6.5.3.

6.4.3 Main Analysis

In this section, we present the results of our main analysis, focusing on how varying drone sound levels (Low, Medium, High) and working memory loads (Low (1-back), High (3-back)) impact different aspects of participants' interactions with the drone. This analysis covers their perceptions of the drone and its sound, subjective arousal and task load, proxemic preferences, and task performance. Each of these aspects is discussed in detail in the following paragraphs, and includes a summary of the mean and standard deviation and statistical tests.

To explore the main effects and interactions between Drone Sound Level and Mental Memory Load on responses measured with Likert scale items, such as subjective arousal, perceived annoyance, loudness, threat, awareness of the drone, and the degree to which participants were bothered by its presence, we employed the ARTool package in R. This package uses the Aligned Ranks Transformation (ART) method to prepare the data for a non-parametric factorial ANOVA [379]. Post-hoc pairwise comparisons with Holm adjustment were performed using the extended ART-C procedure [112]. These methods are particularly suitable for analyzing Likert-type data, which is ordinal in nature [379].

For continuous data, including performance metrics, maintained distance, and NASA TLX scores, a two-way analysis of variance (ANOVA) was conducted to investigate the impact of the independent variables—Drone Sound Level (*Low, Medium, High*) and Mental Memory Load (*Low (1-back), High (3-back)*)—on these dependent variables. We verified the assumptions of normality (Shapiro-Wilk test, $p > 0.05$) and homogeneity of variances (Levene's test, $p > 0.05$). For cases where the sphericity assumption was violated, as determined by Mauchly's test, we applied the Greenhouse-Geisser correction. All p-values were adjusted using the Holm-Bonferroni method for multiple comparisons. Given that even small variations in distance could remain significant in the context of our work, using a more conservative method like Bonferroni might increase the risk of Type II errors, potentially leading us to overlook important effects. Therefore, Holm-Bonferroni offers a balanced approach, allowing us to control for Type I errors while retaining the power to detect subtle but relevant differences. As the effect size measure, we use generalized eta squared (noted as η_G^2), which is recommended in recent literature for ANOVA analyses [217, 275].

> Each paragraph (i.e., Sound Perception, Drone Presence, Subjective Arousal & Maintained Distance, Performance Metrics and NASA-TLX) concludes with a colored box like this, offering a summary of the key findings and guiding the reader to other relevant results or associated discussion sections.

Sound Perception Participants' perception of the drone's sound—measured in terms of annoyance, loudness, and threat perception—was assessed using a 10-point Likert scale (see Methodology subsection 6.3.2). This assessment allowed us to examine the impact of the three drone sound levels and two levels of mental memory load on participants' responses. A summary of the results is provided in Table 6.6, while Figure 6.6 visually depicts the differences in perceived loudness and annoyance across the different conditions. Together with the qualitative analysis of interviews presented later, these results offer a comprehensive insight into how participants perceived the drone's sound within the context of our study.

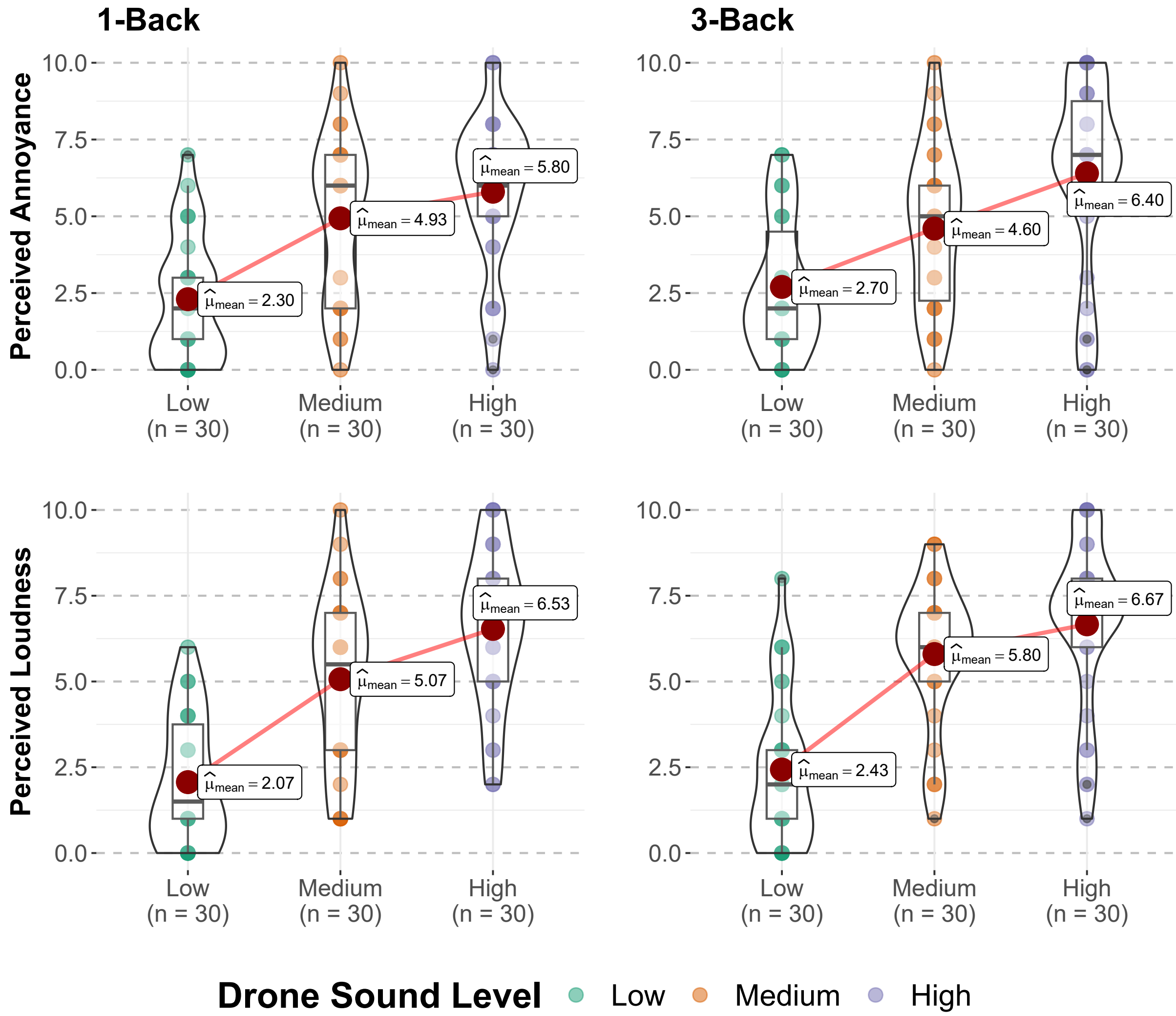
Table 6.6: **Summary of Sound Perception metrics** (Perceived Annoyance, Loudness, and Threat), showing the mean (M) and standard deviation (SD) for each variable across the two working memory load conditions (Low (1-back) and High (3-back)) and the three sound level conditions (Low, Medium, High). The results of the ART ANOVA are provided, with significance codes as follows: * p < 0.05, ** p < 0.01, *** p < 0.001. The final column indicates which levels are significantly different, with L, M, and H referring to the sound levels (Low, Medium, High), and 1 and 3 representing the n-back task conditions.

		1-Back			**3-Back**		
		Low	**Medium**	**High**	**Low**	**Medium**	**High**
Perceived Annoyance	*M*	2.3	4.93	5.8	2.7	4.6	6.4
	SD	2.04	2.66	2.48	2.17	2.57	3.04
Perceived Loudness	*M*	2.07	5.07	6.53	2.43	5.8	6.67
	SD	1.84	2.48	2.24	2.18	2.07	2.48
Perceived Threat	*M*	2.33	4	5.17	2.43	4.07	4.73
	SD	2.29	2.72	2.90	2.43	2.52	3.06

		F Test	**p.value (sign.)**	**post.hoc**
Perceived Annoyance ART-Anova	Sound Level	$F(2,145) = 66.80$	< 2e-16 (***)	L-M, L-H, M-H
	N-Back	$F(1,145) = 0.21$	0.64797	
	Interaction	$F(2,145) = 1.52$	0.223	
Perceived Loudness ART-Anova	Sound Level	$F(2,145) = 122.41$	< 2e-16 (***)	L-M, L-H, M-H
	N-Back	$F(1,145) = 4.90$	0.028 (*)	1-3
	Interaction	$F(2,145) = 0.63$	0.54	
Perceived Threat ART-Anova	Sound Level	$F(2,145) = 41.74$	4.8e-15 (***)	L-M, L-H, M-H
	N-Back	$F(1,145) = 0.13$	0.71	
	Interaction	$F(2,145) = 0.86$	0.42	

- **Perceived Annoyance** Participants' perceived annoyance increased progressively from Slightly Annoying (< 4) at the Low sound level ($M_{1-back} = 2.3$, $M_{3-back} = 2.7$), to lower Moderately Annoying (<5) at the Medium sound level ($M_{1-back} = 4.93$, $M_{3-back} = 4.6$),

Figure 6.6: Boxplot and violin plots illustrating participants' perceived annoyance and loudness for the three drone sound level conditions in both task condition. Both significantly increased from the low to high sound level condition, the drone was perceived as significantly louder during the 3-back task compared to the 1-back. No interation effects was observed.



and further to upper Moderately Annoying (>5) at the High sound level (M_{1-back} = 5.8, M_{3-back} = 6.4). Annoyance ratings increased from the 1-back to the 3-back condition for the Low and High sound levels but decreased for the Medium sound level. Statistical analysis revealed a significant effect of drone sound level on perceived annoyance ($F(2,145)$ = 66.8, $p < 0.001$). Post-hoc comparisons showed that the High sound level (M=6.1) induced significantly more annoyance than both the Medium (M=4.77, $p < 0.001$) and Low sound levels (M=2.5, $p < 0.001$), with the Medium level also inducing significantly more annoyance than the Low level ($p < 0.001$). No significant main effect of task condition or interaction between task and sound level was observed.

- **Perceived Loudness** Similar to perceived annoyance, participants' perceived loudness increased progressively from Slightly Annoying (< 4) at the Low sound level (M_{1-back} = 2.07, M_{3-back} = 2.43), to Moderately Annoying at the Medium sound level (M_{1-back} = 5.07, M_{3-back} = 5.8), and further to upper Moderately Annoying at the High sound level (M_{1-back} = 6.53, M_{3-back} = 6.67). Loudness ratings slightly but consistently increased from the 1-back to the 3-back condition for each sound level conditions. Statistical analysis revealed a significant effect of drone sound level on perceived annoyance ($F(2,145)$ = 122.41, $p < 0.001$). Post-hoc comparisons showed that the High sound level (M=6.6) was significantly louder than both the Medium (M=5.43, $p < 0.001$) and Low sound levels (M=2.25, $p < 0.001$), with the Medium level also being perceived as louder than the Low level ($p < 0.001$). Interestingly, a significant main effect of task condition was also found (($F(1,145)$ = 4.90, p = 0.028), with the loudness being significantly higher in the high mental memory load condition during the 3-back task (M=4.97) compared to the low mental memory load condition during the 1-back task (M=4.56). No significant interaction effect between task and sound level was observed.

- **Perceived Threat** Participants' perceived threat from the drone's sound progressively increased from Slightly Threatening (scores < 4) at the Low sound level (M_{1-back} = 2.33, M_{3-back} = 2.43), to Moderately Threatening (scores < 5) at the Medium sound level (M_{1-back} = 4, M_{3-back} = 4.07), and continued to rise, though remaining in the moderate range, at the High sound level (M_{1-back} = 5.17, M_{3-back} = 4.73). Threat perception slightly increased from the 1-back to the 3-back condition at the Low and Medium sound levels but decreased at the High sound level. Statistical analysis revealed a significant effect of drone sound level on perceived threat ($F(2,145)$ = 41.74, $p < 0.001$). Post-hoc comparisons indicated that the High sound level (M=4.95) was perceived as significantly more threatening than both the Medium (M=4.03, $p < 0.001$) and Low sound levels (M=2.38, $p < 0.001$), with the Medium level also perceived as significantly more threatening than the Low level ($p < 0.001$). No significant main effect of the task condition or interaction between task and sound level was observed.

Sound Perception – Summary

- Our results (see Table 6.6) demonstrate that the drone's sound level significantly influences perceptions of annoyance, loudness, and threat. Medium and High sound levels were associated with moderate to high levels of annoyance and threat, indicating potential challenges with these intensities. In contrast, the Low sound level led to only slight annoyance and threat, making it a more acceptable option. These findings, discussed further in subsection 6.5.1, suggest that reducing drone sound levels could alleviate perceived annoyance and threat, enhancing user experience and minimizing negative reactions in environments where drones are deployed.

- Another noteworthy finding is that participants perceived the drone as significantly louder during the more cognitively demanding 3-back task compared to the 1-back task. This suggests that contextual factors, such as task difficulty, play a crucial role in the perception of drone sound. As discussed in subsection 6.5.1, this finding addresses a gap identified in previous research by highlighting the influence of contextual factors on the perception of drone noise.

- Qualitative analysis of post-experiment interviews (see subsection 6.4.4) further enriches these results, providing deeper insights into how drone sounds are perceived at different intensity levels during task performance. These qualitative findings offer a more nuanced understanding of participants' experiences and perceptions, complementing the quantitative data.

Drone Presence Impact of drone's presence was assessed by evaluating how noticeable and bothersome participants found the drone, in addition to its sound. This evaluation focused on participants' awareness of the drone and their level of discomfort or disruption caused by its presence. These aspects provide a complementary perspective to the assessment of the drone's sound and are summarized in Table 6.7.

- **Awareness** Participants' awareness of the drone increased progressively across sound levels, starting from lower Moderately Aware at the Low sound level (M_{1-back} = 4.03, M_{3-back} = 4.33), to upper Moderately Aware at the Medium sound level (M_{1-back} = 6, M_{3-back} = 6.4), and reaching Very Aware at the High sound level, especially in the 3-back condition (M_{1-back} = 6.4, M_{3-back} = 7.1). Awareness consistently increased from the 1-back to the 3-back condition at each sound level. Statistical analysis revealed a significant effect of drone sound level on awareness ($F(2,145) = 22.77$, $p < 0.001$). Post-hoc comparisons indicated that participants were significantly less aware of the drone in the Low sound level (M=4.18) condition compared to both the Medium (M=6.12, $p < 0.001$) and High (M=6.75, $p < 0.001$) sound levels. Despite the consistent differences in mean awareness between task conditions, no significant main effect of task condition or interaction between task and sound level was observed.

- **Bother** Participants' level of bother from the drone's presence increased progressively, starting from Slightly Bothered (< 4) at the Low sound level (M_{1-back} = 2.43, M_{3-back} = 3.13), advancing to Moderately Bothered at the Medium sound level (M_{1-back} = 4.73, M_{3-back} = 4.63), and reaching the upper range of Moderately Bothered at the High sound level (M_{1-back} = 5.63, M_{3-back} = 6.17). Bother ratings slightly increased from the 1-back to the 3-back condition for the Low and High sound levels but decreased for the Medium sound level. Statistical analysis revealed a significant effect of drone sound level

Table 6.7: **Summary of Drone Presence metrics** (Awareness, and Bother), showing the mean (M) and standard deviation (SD) for each variable across the two working memory load conditions (Low (1-back) and High (3-back)) and the three sound level conditions (Low, Medium, High). The results of the ART ANOVA are provided, with significance codes as follows: * p < 0.05, ** p < 0.01, *** p < 0.001. The final column indicates which levels are significantly different, with L, M, and H referring to the sound levels (Low, Medium, High), and 1 and 3 representing the n-back task conditions.

		1-Back			3-Back		
		Low	**Medium**	**High**	**Low**	**Medium**	**High**
Awareness	*M*	4.03	6	6.4	4.33	6.23	7.1
	SD	2.88	2.68	2.63	2.99	2.99	2.55

		F Test	**p.value (sign.)**	**post.hoc**
ART-Anova	Sound Level	$F(2,145) = 22.77$	2.52e-15 (***)	L-M, L-H
	N-Back	$F(1,145) = 2.9$	0.09	
	Interaction	$F(2,145) = 0.25$	0.78	

Bother	*M*	2.43	4.73	5.63	3.13	4.63	6.17
	SD	2.24	2.92	2.41	2.84	2.88	3.30

ART-Anova	Sound Level	$F(2,145) = 40.97$	7.9e-15 (***)	L-M, L-H, M-H
	N-Back	$F(1,145) = 0.25$	0.515	
	Interaction	$F(2,145) = 0.66$	0.517	

on perceived bother ($F(2,145) = 40.97$, $p < 0.001$). Post-hoc comparisons showed that participants were significantly more bothered by the drone in the High sound level condition (M = 5.9) compared to both the Medium (M = 4.68, $p < 0.001$) and Low sound levels (M = 2.78, $p < 0.001$), with the Medium level also being perceived as more bothersome than the Low level ($p < 0.001$). No significant main effect of task condition or interaction between task and sound level was observed.

Drone Presence – Summary

- Our results (see Table 6.7) indicate that the drone's sound level significantly affects individuals' awareness of the drone and how much they were bothered by its presence. As with previous measures, the low sound level significantly reduced these effects. While participants remained moderately aware of the drone even at the lowest sound level, their level of annoyance shifted from moderate at the Medium and High sound levels to only slight at the low sound level. This suggests that reducing drone sound levels to a certain threshold could help minimize its intrusion, making it less likely to draw attention or bother people in inhabited spaces.

- In our study, since the visual presence of the drone was limited and participants were focused on their task, the sound it emitted largely defined its presence. However, qualitative analysis from post-experiment interviews suggests that the visual presence of the drone, still played a role by making the drone feel more tangible and "there," beyond just being a source of sound (see subsection 6.4.4).

Subjective Arousal & Maintained Distance To evaluate the role of proxemic behavior in arousal regulation, we measured the distance participants maintained from the drone under each set of conditions, following their physiological arousal ratings. We analyzed how these two measures varied across conditions and examined their interrelationship. Figure 6.7 visualizes these measures, with detailed results in Table 6.8 and the correlation between them illustrated in Figure 6.8.

Table 6.8: **Summary of Subjective Arousal and Maintained Distance measures and statistical results.**

		1-Back			3-Back		
		Low	**Medium**	**High**	**Low**	**Medium**	**High**
Subjective Arousal	*M*	3.23	4.37	4.63	3.9	5	5.3
	SD	2.5	2.98	3.1	2.4	2.59	2.91

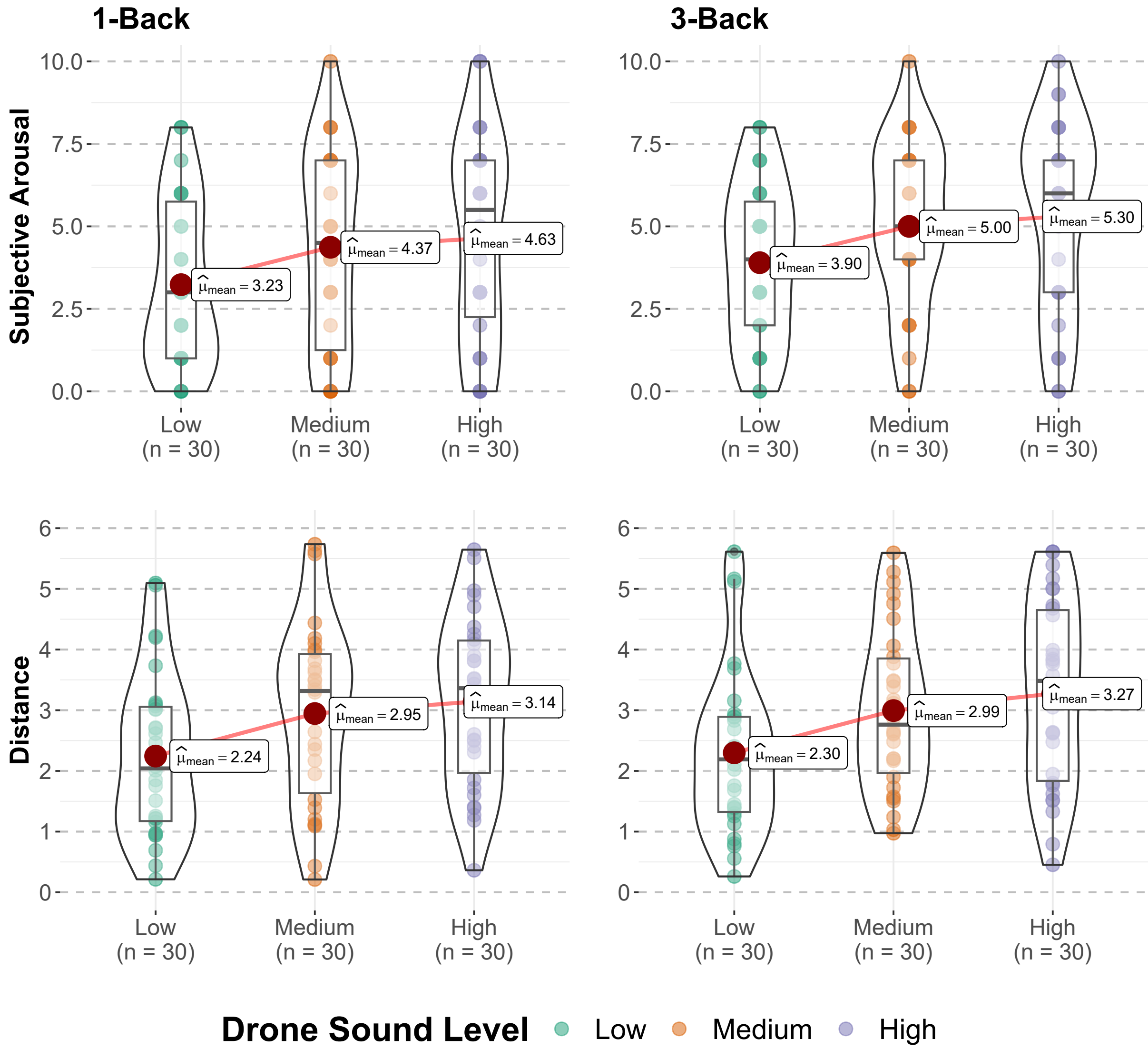
		F Test	p.value (sign.)	post.hoc
ART-Anova	Sound Level	$F(2,145) = 14.92$	1.28e-06 (***)	L-M, L-H
	N-Back	$F(1,145) = 5.71$	0.018 (*)	1-3
	Interaction	$F(2,145) = 0.004$	0.996	

		1-Back Low	1-Back Medium	1-Back High	3-Back Low	3-Back Medium	3-Back High
Maintained Distance	*M*	2.24	2.95	3.14	2.30	2.99	3.27
(meters)	*SD*	1.40	1.34	1.50	1.53	1.36	1.33

		F Test	p.value (sign.)	post.hoc
Anova	Sound Level	$F(1.39,40.33) = 18.12$	6.72e-05 (***)	L-M, L-H, M-H
	N-Back	$F(1,29) = 0.359$	≈ 1	
	Interaction	$F(2,58) = 0.089$	≈ 1	

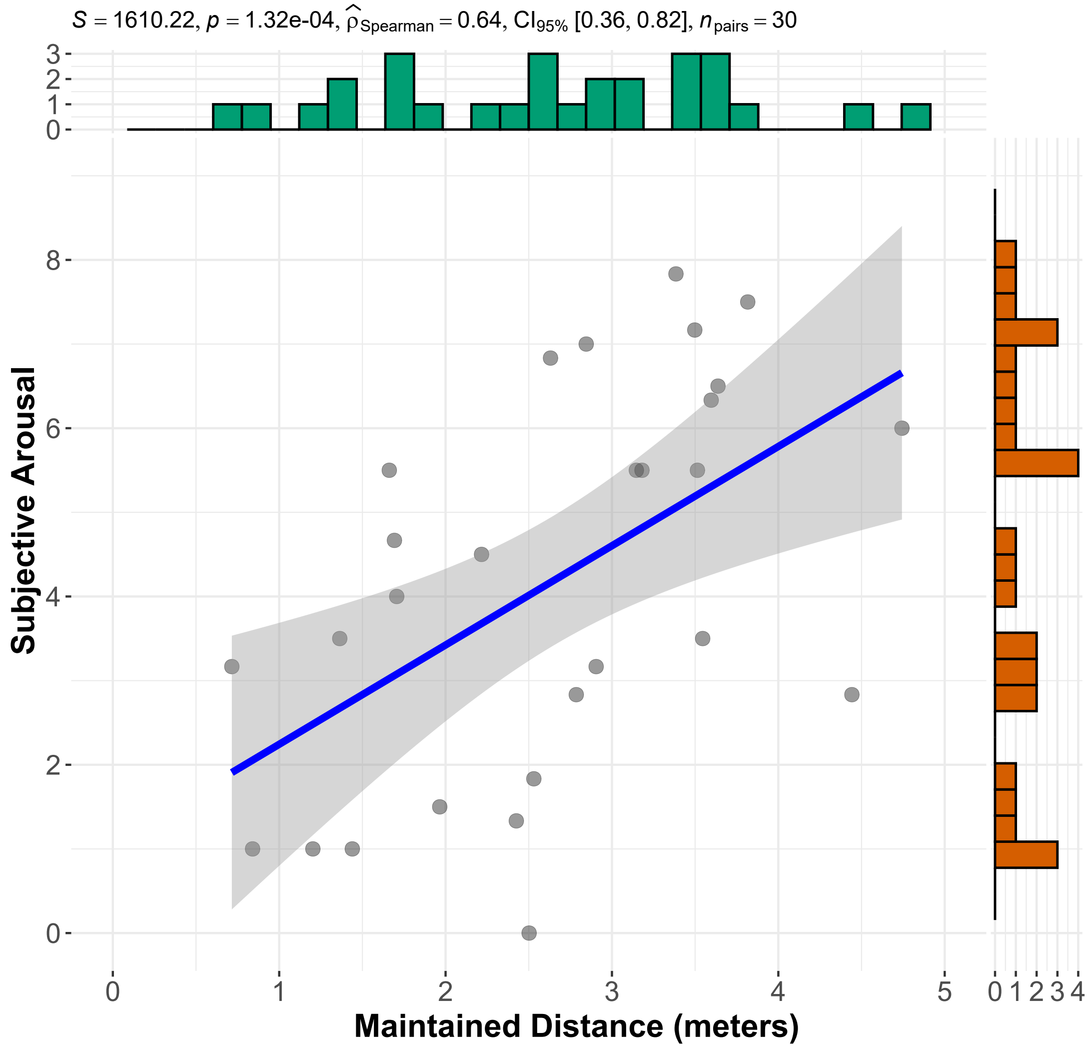
- **Subjective Arousal** Participants rated their subjective physiological arousal from 0 (minimum) to 10 (maximum) for each condition. On average, arousal increased progressively across sound levels, starting from relatively low to moderate levels (<4) for the Low sound level condition (M_{1-back} = 3.23, M_{3-back} = 3.90). This was followed by moderate arousal

Figure 6.7: Boxplot and violin plots illustrating participants' subjective arousal and maintained distance for the three drone sound level conditions in both task condition. Both significantly increased from the low to high sound level condition in a similar trend.



levels with the Medium sound level ($M_{1-back} = 4.37$, $M_{3-back} = 5.00$), and a slight increase at the High sound level ($M_{1-back} = 4.63$, $M_{3-back} = 5.30$). Overall, participants' subjective arousal increased from the 1-back (M = 4.08) to the 3-back (M = 4.73) and showed a consistent slight increase across sound levels. Statistical analysis revealed a significant effect of drone sound level on arousal ($F(2,145) = 14.92$, $p < 0.001$). Post-hoc comparisons indicated that arousal was significantly lower for the Low sound level condition (M = 3.57) compared to both the Medium (M = 4.68, p = 9.78e-05) and High (M = 4.97, p = 2.72e-06) sound levels, with no significant difference between the Medium and High levels (p = 0.35). Additionally, a significant main effect of task condition was found ($F(1,145)$ = 5.71, $p = 0.018$), with greater arousal in the high mental load condition during the 3-back

Figure 6.8: Scatterplot of average subjective arousal and maintained distance measures for each participant, overlaid with the results of a Spearman correlation test. The analysis reveals a statistically significant moderate positive correlation (p=1.32e-04, r_s=0.64) between participants' arousal levels and the distance they chose to maintain from the drone.



task compared to the low mental load condition during the 1-back task. No significant interaction effect between task and sound level was observed.

- **Maintained Distance** Participants' distance from the drone increased with the loudness of the drone. Starting with an average initial distance of approximately 2.45 meters, participants tended to approach the drone slightly in the Low sound level condition during both task conditions (M_{1-back} = 2.24, M_{3-back} = 2.30). However, in the Medium and High sound level conditions, participants moved away from the drone, with distances increasing from the Medium (M_{1-back} = 2.95, M_{3-back} = 2.99) to the Loud (M_{1-back} = 3.14, M_{3-back} = 3.27) conditions. Overall, the maintained distance increased from the 1-back (M = 2.78) to the 3-back (M = 2.86) and showed a consistent slight increase across sound levels. Statistical analysis indicated a significant effect of drone sound level on maintained distance

($F(1.39, 40.33) = 18.120$, $p < 0.001$, η^2_G=0.076). Post-hoc tests revealed that participants maintained a significantly greater distance in the High sound level condition (M = 3.21 m) compared to both the Medium (M = 2.97 m, $p = 0.035$) and Low sound levels (M = 2.27 m, p=2.32e-04), with the Medium level also resulting in a greater distance than the Low level ($p = 2.86e - .4$). No significant main effect of task condition or interaction between task and sound level was found.

Arousal and Distance – Summary

- Our results (see Table 6.7) indicate that both subjective arousal and the distance participants maintained from the drone were significantly influenced by the drone's sound levels. The lowest sound level resulted in significantly lower subjective arousal compared to both medium and high sound levels. Interestingly, there was no significant difference in arousal between the medium and high sound levels, suggesting the presence of a threshold below which subjective arousal decreases more sharply, rather than following a linear relationship with sound intensity. This pattern was mirrored in participants' proxemic behavior, with greater distances being maintained as the drone's sound level increased. This behavior was likely a strategy to mitigate the perceived intensity of the drone's presence, as the sound naturally decreases the farther one moves away from the drone.

- As anticipated, the more demanding 3-back task resulted in increased subjective arousal compared to the 1-back task. However, this heightened arousal did not translate into significantly greater distances maintained between the two task conditions. Participant feedback on their distance adjustments revealed diverse behavioral responses, which may account for the overall non-significant effect (see subsection 6.4.4).

- We also found a moderate positive correlation between subjective arousal and maintained distance (see Figure 6.8), indicating that participants who felt more aroused by the drone's presence tended to move further away. This relationship supports the role of proxemic behavior as a potential coping mechanism for managing arousal in response to drone noise, a topic further discussed in subsection 6.5.5.

Performance Metrics To evaluate the impact of varying drone sound levels on task performance, we assessed participants' performance during the n-back task using two key metrics: reaction time and accuracy. We examined how these metrics varied across different sound conditions with detailed results in Table 6.9. Reaction time and accuracy provide objective metrics with quantifiable data on how performance varies under different sound conditions and complement the NASA-TLX, presented later, which adds a subjective perspective by capturing participants' personal evaluations of their task experience.

Table 6.9: **Summary of Subjective Arousal and Maintained Distance measures and statistical results.**

		1-Back			3-Back		
		Low	Medium	High	Low	Medium	High
Reaction Time (seconds)	*M*	0.622	0.629	0.628	0.934	0.932	0.934
	SD	0.144	0.166	0.143	0.282	0.287	0.270

		F Test	p.value (sign.)	post.hoc
Anova	Sound Level	$F(2,58) = 0.591$	≈1	
	N-Back	$F(1,29) = 60.665$	4.11e-08 (***)	1-3
	Interaction	$F(2,58) = 0.461$	≈1	

		1-Back			3-Back		
		Low	Medium	High	Low	Medium	High
Accuracy (%)	*M*	90.4	90.3	90.6	69.5	69.7	70.8
	SD	4.7	6.44	5.12	11	12.6	9.37

		F Test	p.value (sign.)	post.hoc
Anova	Sound Level	$F(2,58) = 0.377$	≈1	
	N-Back	$F(1,29) = 178.507$	1.917e-13 (***)	1-3
	Interaction	$F(2,58) = 0.14$	≈1	

- **Reaction Time** Participants' reaction times consistently increased from the 1-back task (M_{low} = 0.622s, M_{medium} = 0.629s, M_{high} = 0.628s), where average times were below 70 ms, to nearly 1 second during the 3-back task (M_{low} = 0.934s, M_{medium} = 0.932s, M_{high} = 0.934s). Overall, the average reaction time remained very consistent across the Low (M = 0.76s), Medium (M = 0.78s), and High sound levels (M = 0.78s) and within task conditions. Statistical analysis revealed a significant effect of task condition on reaction time ($F(1, 29) = 60.665$, $p < 0.001$, η^2_G= 0.31), with longer reaction times in the high mental load condition during the 3-back task (M = 0.92s) compared to the low mental load condition during the 1-back task (M = 0.62s). No significant main effect of drone sound level or interaction between task and sound level was observed.

- **Accuracy** Participants' accuracy decreased by approximately 20% from the 1-back task (M_{low} = 90.4%, M_{medium} = 90.3%, M_{high} = 90.6%) to the 3-back task (M_{low} = 69.5%, M_{medium} = 69.7%, M_{high} = 70.8%). Overall, the average accuracy remained very consistent between the Low (M =80.73%), Medium (M = 79.97%), and High sound levels (M = 80.01%) and within task conditions. Statistical analysis revealed a significant effect of task condition on accuracy ($F(1, 29) = 178.507$, $p < 0.001$, η^2_G= 0.59), with lower accuracy in the high mental load condition during the 3-back task (M = 90.45%) compared to the low mental load condition during the 1-back task (M = 70.03%). No significant main effect of drone sound level or interaction between task and sound level was observed.

Performance Metrics – Summary

- Our results (see Table 6.9) reveal a significant difference in reaction time and accuracy between the 1-back and 3-back tasks, underscoring the increased difficulty and mental workload associated with the more demanding 3-back task, as previously noted in Figure 6.5. However, the sound levels did not significantly affect task performance, with average reaction times and accuracy remaining consistent across different sound conditions.

- While drone sound exposure did not directly impact participants' performance metrics, it influenced their subjective experience of the task. This is further explored in the following results section, which details findings from the NASA-TLX subscales. Together, these measures provide a comprehensive view of how varying levels of drone sound exposure affect both objective task performance and subjective task experience within the context of our study. This topic is explored in more detail in subsection 6.5.2.

NASA-TLX The NASA-TLX adds a subjective perspective by capturing participants' personal evaluations of their task experience after each condition and complements the earlier presented objective measures of reaction time and accuracy, which provide quantifiable data on how performance varies under different sound conditions. By combining these measures, we aimed to investigate how drone sound exposure impacts both the subjective experience and objective performance of tasks at varying levels of difficulty.

- **Mental** The mental workload scores increased across both the 1-back (M_{low} = 32, M_{medium} = 49.1, M_{high} = 49.4) and 3-back tasks (M_{low} = 70.1, M_{medium} = 77.3, M_{high} = 78.4) as the sound level increased. Overall, the 3-back task resulted in higher mental workload than the 1-back task. This trend indicates that both higher sound levels and greater cognitive load (moving from 1-back to 3-back) led to increased perceived mental workload. Statistical analysis revealed significant main effects of task condition ($F(1, 29) = 42.957$, $p < 0.001$, $\eta^2_G = 0.358$), sound level ($F(2, 58) = 9.053$, $p < 0.001$, $\eta^2_G = 0.071$), and a significant interaction effect between the two variables ($F(2, 58) = 4.021$, $p = 0.023$, $\eta^2_G = 0.011$). Further examination showed that the drone's sound levels significantly influenced perceived mental workload only during the 1-back task ($F(2, 58) = 11.0$, $p = 0.000178$, $\eta^2_G = 0.097$), but not during the 3-back task. Post hoc tests indicated that the Low sound level induced significantly lower mental workload compared to both Medium ($p = 0.00024$) and High ($p = 0.003$) sound levels. In contrast, task condition significantly influenced

Table 6.10: **Summary of NASA-TLX measures and statistical results.** Only significant main effects and interactions are reported.

NASA-TLX

		1-Back			3-Back		
		Low	**Medium**	**High**	**Low**	**Medium**	**High**
Mental	*M*	32	49.1	49.4	70.1	77.3	78.4
	SD	20.9	26.1	28	23.6	12.8	13.9
		F Test		**p.value (sign.)**		**post.hoc**	
Anova	Sound Level	$F(2,58) = 9.053$		7.580e-04 (***)		L-M, L-H	
	N-Back	$F(1,29) = 42.957$		1.059e-06 (***)		1-3	
	Interaction	$F(2,58) = 4.021$		0.023 (*)		**1**(L-M, L-H)	
						L(1-3), **M**(1-3), **H**(1-3)	
Physical	*M*	21.9	26.5	26	25.1	32.6	30.9
	SD	20.5	22.7	23	19.8	24.2	23.2
Anova	Sound Level	$F(2,58) = 4.586$		0.042 (*)		L-M	
Pressure	*M*	33	40	45.1	57.4	70.1	68
	SD	21.5	20.5	24.8	28	17.6	17.8
Anova	Sound Level	$F(1.58, 45.76) = 8.119$		0.004 (**)		L-M, L-H	
	N-Back	$F(1,29) = 40.368$		1.82e-06 (***)		1-3	
Performance	*M*	73	68.60	68.9	37.6	46.7	35.23
	SD	20.9	25.1	22.7	20.3	21.8	16.1
Anova	N-Back	$F(1,29) = 53.383$		1.434e-07 (***)		1-3	
Effort	*M*	37.9	48.8	50.7	72.1	75	77.3
	SD	23.2	25.4	26.3	19.5	14.1	14.4
Anova	Sound Level	$F(1.66,48) = 7.433$		0.006 (**)		L-M, L-H	
	N-Back	$F(1,29) = 35.542$		5.31e-06 (***)		1-3	
Frustration	*M*	30.3	46	51.4	56.5	60.5	64.1
	SD	24.3	30.5	27.6	25.8	22.7	25.2
Anova	Sound Level	$F(2,58) = 9.694$		0.0007 (***)		L-H	
	N-Back	$F(1,29) = 27.012$		4.41e-05 (***)		1-3	

perceived mental workload at each sound level, with an overall mean of $M = 44.94$ for the 1-back task and $M = 74.89$ for the 3-back task.

- **Physical** Participants' physical workload increased from the 1-back ($M_{low} = 21.9$, $M_{medium} = 26.5$, $M_{high} = 26.0$) to the 3-back ($M_{low} = 25.1$, $M_{medium} = 32.6$, $M_{high} = 30.9$) task for each sound level. Across sound levels, the medium sound level (M = 29.57) was associated with higher physical workload compared to both the low (M = 23.52) and high (M = 28.43) sound levels. Despite these increases, the physical workload remained relatively low overall, indicating that participants did not experience excessive physical strain. Statistical analysis revealed a significant main effect of sound level on physical workload ($F(2, 58) = 4.586$, $p = 0.042$, $\eta^2_G = 0.014$), with post hoc tests showing that the medium sound level resulted in significantly higher physical workload compared to the low sound level ($p = 0.003$). No significant main effect of task condition or interaction between task condition and sound level was found.

- **Pressure** Participants' perceived pressure increased from the 1-back (M_{low} = 33, M_{medium} = 40, M_{high} = 45.1) to the 3-back (M_{low} = 57.4, M_{medium} = 70.1, M_{high} = 68.0) task across all sound levels. Across sound levels, pressure rose from the low (M = 45.17) to the medium (M = 55.07) and high (M = 56.58) sound levels, although it remained similar between the medium and high levels. Overall, participants experienced a range of pressure from low (e.g., 33) to moderately high (e.g., 70.1) depending on the task and sound conditions. Statistical analysis revealed a significant main effect of both sound level ($F(1.58, 45.76) = 8.119$, $p = 0.004$, η^2_G= 0.052) and task condition ($F(1, 29) = 40.368$, p = 1.821e-6, η^2_G = 0.262) on perceived pressure. Post hoc tests indicated that the low sound level resulted in significantly lower pressure compared to both the medium ($p = 0.032$) and high ($p = 0.034$) sound levels. Additionally, the 3-back task (M = 65.17) was associated with significantly higher pressure than the 1-back task (M = 39.38). No significant interaction between task condition and sound level was found.

- **Performance** Participants' perceived performance, or their self-assessment of how well they completed the task, decreased from the 1-back (M_{low} = 73, M_{medium} = 68.6, M_{high} = 68.9) to the 3-back (M_{low} = 37.6, M_{medium} = 46.7, M_{high} = 35.2) task across all sound levels. This shift indicates a move from a moderately high perception of performance to a notably lower one. Across sound levels, the overall performance perception remained relatively consistent, with no significant differences between low (M = 55.3), medium (M = 57.7), and high (M = 52.1) sound levels. Statistical analysis revealed a significant main effect of task condition ($F(1, 29) = 53.383$, p = 1.434e-07, η^2_G= 0.343), with significantly lower perceived performance in the 3-back task (M = 39.8) compared to the 1-back task (M = 70.2). No significant main effect of sound level or interaction between task condition and sound level was observed.

- **Effort** Participants' perceived effort, or how hard they believed they had to work to achieve their performance, increased with sound levels in both the 1-back (M_{low} = 37.9, M_{medium} = 48.8, M_{high} = 50.7) and 3-back (M_{low} = 72.1, M_{medium} = 75.0, M_{high} = 77.3) tasks. Effort also increased from the 1-back task (M = 45.8) to the 3-back task (M = 74.8).

Statistical analysis revealed significant main effects of both sound level ($F(1.66, 48)$ = 8.119, p = 0.006, η^2_G= 0.033) and task condition ($F(1, 29)$ = 5.542, p = 5.31e-06, η^2_G= 0.329) on perceived effort. Post hoc tests showed no significant differences between sound levels, although effort ratings were lower at the Low sound level (M = 55.0) compared to the Medium (M = 61.4) and High (M = 64.0) levels. Further analysis revealed significant differences under the 1-back task condition with higher effort reported at Medium (p = 0.002) and High (p = 0.011) sound levels compared to Low. Additionally, the 3-back task (M = 74.8) required significantly more effort than the 1-back task (M = 45.8). No significant interaction between task condition and sound level was observed.

- **Frustration** Participants' frustration increased with sound levels in both the 1-back (M_{low} = 30.3, M_{medium} = 46, M_{high} = 51.4) and 3-back (M_{low} = 56.6, M_{medium} = 60.5, M_{high} = 64.1) tasks. Additionally, frustration increased from the 1-back task (M = 42.57) to the 3-back task (M = 60.37). Statistical analysis revealed significant main effects of both sound level ($F(2, 58)$ = 9.694, p = 0.000699, η^2_G= 0.329) = 0.052) and task condition ($F(1, 29)$ = 27.012, p = 0.0000441, η^2_G= 0.329)= 0.107) on frustration. Post hoc tests indicated that frustration was significantly lower in the low sound level condition (M = 43.4) compared to the high sound level (M = 57.77, p = 0.001). Furthermore, the 3-back task (M = 60.37) was significantly more frustrating than the 1-back task (M = 42.57). No significant interaction between task condition and sound level was observed.

NASA-TLX – Summary

- Our results (see Table 6.10) reveal significant changes in perceived mental workload, pressure, performance, effort, and frustration between the 1-back and 3-back tasks, reflecting the substantial increase in difficulty and cognitive demand.
- Of particular interest is the effect of drone sound levels on participants' subjective experience of task performance. Although the effect of sound levels was less pronounced compared to task difficulty, as indicated by smaller effect sizes, drone sound significantly impacted participants' mental and physical workload, perceived pressure, frustration levels, and effort. Specifically, the low sound level condition consistently resulted in significantly lower scores across these dimensions compared to both medium and high sound levels, which did not differ significantly from each other. Furthermore, a significant interaction effect between sound levels and task conditions revealed that drone sound levels significantly affected mental workload only during the 1-back task. This suggests that individuals' responses to drone sound may vary based on the cognitive demands of the task.
- Overall, while drone sound levels did not directly affect objective performance metrics, they influenced the subjective experience of task performance, indicating that

drone noise can have a notable impact on how individuals perceive their task-related workload and stress. This topic is further explored in subsection 6.5.2.

6.4.4 Qualitative Analysis

In the post-experiment interviews, participants were asked to elaborate on their reasoning for selecting specific distances from the drone, their perceptions of the drone's sound, and any noticeable differences between varying sound levels. They were also invited to reflect on how the difficulty of the task influenced their perception of the drone's sound and its impact on their task performance. From these discussions, three main categories emerged, which are detailed below.

To analyze and categorize the themes derived from participants' feedback, we utilized an affinity diagram approach, as previously applied in our research [57, 59]. This method is effective for organizing extensive qualitative data, such as responses from semi-structured interviews, into coherent themes or categories [245]. By grouping related responses and identifying recurring patterns, we were able to gain deeper insights into participants' subjective experiences and perceptions regarding drone sound and task difficulty.

Proxemic Motivation

Participants were asked to share their motivations for choosing specific distances from the drone. Many cited the desire to mitigate the negative effects of the drone's sound, describing it as irritating, annoying, or hurtful. One participant interestingly noted that, despite the annoyance, their ability to perform the task remained unaffected. However, others directly linked their distance adjustments to task performance, explaining that they moved away to reduce the drone's noise and enhance their focus. For example, Participant 20 shared:

> "My hearing is quite sharp. So when I'm trying to focus on doing something and I'm also trying to balance the noise level, my brain is kind of feeling a bit overwhelmed. So I can't really focus as much as I want, which then increases the pressure in your head, which then makes the task more difficult. [...] So when you move away from that noise, you can kind of start to think a bit clearer and start to do the task."

One participant mentioned finding an optimal sound level that would help maintain concentration. For a subset of participants, task difficulty influenced their distance choice; they reported needing to reduce the drone's noise more during the more challenging 3-back task compared to the 1-back task, as higher levels of focus and mental resources were required. Additionally, several participants mentioned that, if space permitted, they would have preferred to be even farther from the drone. One participant mentioned not moving too far because it seemed unreasonable, hinting at potential social norms. Another participant reported that the chosen distance was acceptable for short exposures but would differ for longer durations. Contrastingly, another group of participants indicated that the drone's sound did not significantly impact them, prompting them to stay as close to the drone as possible. These participants reported becoming accustomed to the sound over time or being too focused on the task for the noise to be a distraction. However, one participant did mention that while the sound itself was manageable, the visual presence of the drone combined with the noise made them more aware of its presence, motivating them to move away.

Sound Impact

Participants provided insightful feedback on how the drone's sound impacted them. As expected, many described the drone's noise as particularly distracting, reducing their ability to focus and making the task more challenging, especially for the 3-back task which required more concentration and mental resources. P29 shared "With the louder noise it was harder. Not so much for the 1-back but for the 3-back tasks. [...] I just feel like I have to concentrate a lot more because the noise is quite distracting." and P3 said "I think I missed a few because I could hear the noise". Interestingly, some participants reported that this impact decreased over time as they became accustomed to the sound. Others stated they were not affected by the drone's noise and managed to filter it out while performing their tasks. This variation could be attributed to differences in participants' backgrounds, individual noise sensitivity, or ability to concentrate. Some participants mentioned that the task required so much focus that they could block out the sound, although one participant noted that this mental state was unstable; making mistakes could break their concentration and bring the drone's noise back to the forefront of their mind. Surprisingly, the drone's sound was sometimes associated with positive effects, such as increased focus (similar to white noise) and a relaxing effect. Conversely, others reported feelings of anxiety and tiredness, highlighting the individual-dependent effects of sound.

When asked whether different sound levels had varying impacts, participants' feedback again revealed contrasting perceptions. Some participants reported that the low sound level had minimal impact on them, finding it easy to tune out. In contrast, the high sound level was described as more stressful, significantly distracting, and increasing the drone's saliency. However, feedback was mixed, with some participants stating that the low sound level allowed for more mental wandering, while the loud sound helped them focus by masking other potential distractions. The low sound level was often likened to an insect (e.g., a fly), whereas the loud sound was compared to more familiar and positive experiences, such as a ceiling fan. One participant proposed the existence of an optimal sound level, somewhere between the low and high levels, that could provide the concentration benefits of the loud sound without negative associations. Beyond the psychoacoustic properties of the sound, higher-level associations may influence its perception, as suggested in previous work in Human-Drone Interaction (HDI).

Task Difficulty

We also explored how different task difficulties affected participants' experiences. The 3-back task was universally considered harder than the 1-back task. Participants reported that they could still perform the 1-back task even at louder sound levels, whereas the 3-back task was more affected by the noise. As P24 noted, "the 1-back task, I could have it louder because I didn't need as much concentration and focus as I needed for the 3-back." However, the lower focus required for the 1-back task led to more mind wandering and greater attention to external stimuli. P11 described this experience: "I sort of let my guard down... I was like, that sound is really annoying. And then suddenly it's like moving on to the next number and it's like, OK, I didn't really catch." Similarly, P17 observed, "when it was the easy one, I found that actually I got distracted more. It was easier to be distracted when I only had to remember one number than when I was focusing on three." Thus, while the 3-back task increased the impact of the sound due to its higher resource demands, it also heightened participants' focus on the task, potentially enabling them to filter out external stimuli more effectively. In essence, the impact of the sound was more pronounced during the 3-back task, but participants were also better able to mitigate this impact through enhanced concentration although depending on their individual sensitivities.

6.5 Discussion

In this discussion section we broach different subjects aiming to fill the gaps highlighted in the literature with support of our results and previous works. We specifically discuss the interplay between sound perception and task at hand, the impact of individual characteristics on drone's sound perception,

6.5.1 Perception of the Drone's Sound

As noted by Lotinga et al. [242], many studies on drone noise exposure often overlook the broader context in which the sound is experienced. They argue that factors such as "the nature or importance of activities being undertaken" could significantly influence subjective responses to sound exposure. Our study addresses this gap by exploring how varying levels of drone noise affect participants' perceptions while engaging in tasks of differing difficulty.

Sound Levels As anticipated, our results show that varying sound levels significantly affected participants' perceptions of annoyance and loudness, reinforcing the well-established link between noise intensity and these subjective responses [242, 352]. Our study also sheds new light on how loud drone noise influences threat perception. While previous research had suggested this relationship [59], our study provides empirical validation. Additionally, louder drone sounds increased participants' awareness of the drone and made them feel more bothered by its presence, indicating that this aspect of drone's design contributes to the negative perception of drones.

Notably, a clear categorical shift was observed between the low sound level and the medium or high sound levels (see Table 6.6 and Table 6.7). This shift underscores the potential of reducing drone sound levels as an effective strategy to mitigate its negative impact. The distinct difference in perception between the low and higher sound levels suggests that lowering the drone's loudness can substantially diminish its disruptive effects and enhance overall user experience. Thus, prioritizing efforts to decrease the drone's sound level could be a crucial step in minimizing its adverse effects on users. However, achieving the right balance between sound reduction and other factors, such as the drone's informational cues and connotations, remains a complex challenge, as discussed in subsection 6.5.4.

Task Influence The impact of task difficulty on the perception of drone noise revealed nuanced insights. While we initially hypothesized that drone noise would be perceived as more annoying during the more demanding 3-back task—due to its requirement for heightened focus and potential for disruption—our findings did not show significant differences in annoyance levels between tasks. However, two specific dimensions did stand out: participants consistently rated the drone as significantly louder during the 3-back task compared to the 1-back task, and there was an increase in participants' awareness of the drone between these tasks, even though this difference was not statistically significant.

One explanation could be that the 3-back task, which required more cognitive focus, made the drone noise seem more critical and disruptive. Feedback from participants indicated that the 3-back task was more affected by the drone noise, suggesting that the noise became more salient and disruptive as the task's difficulty increased. This shift in perception might have led to a greater awareness and perceived loudness of the drone during the 3-back task.

Despite this heightened awareness, the lack of significant differences in annoyance ratings suggests a more complex interaction. It is possible that during the 3-back task, some participants managed to filter out the noise effectively, reducing its overall disruptive impact and, consequently, the annoyance ratings. In contrast, the 1-back task, which required less cognitive effort, allowed for more mental wandering. Participants may have had more mental bandwidth to reflect on the drone's sound, leading them to rate its annoyance based on its acoustic qualities rather than its disruptive impact. Thus, the absence of significant differences in annoyance ratings might reflect a balance of competing influences. During the 3-back task, the focus on task performance could have led to a lower perception of annoyance despite the increased salience of the drone noise. In contrast, during the 1-back task, the lower cognitive demand might have led to higher annoyance ratings as participants perceived the drone's sound as an unpleasant stimulus. This shifting perception could explain the lack of significant differences in overall annoyance ratings.

6.5.2 Drone's Sound and Task Performance

In our study, we investigated how varying sound intensities of drone noise might influence individuals' objective performance and subjective experiences while completing tasks of differing difficulty levels.

Performance

Based on prior research, we hypothesized that higher noise levels—associated with increased annoyance and heightened arousal—would negatively impact performance, particularly during the more demanding 3-back task, which requires sustained and focused attention [61, 334]. It was reasonable to expect that the additional cognitive load imposed by the noise would exacerbate the challenge of maintaining task accuracy and speed.

Surprisingly, our results did not support this expectation. We found no significant impact of the drone sound conditions on objective performance metrics, such as reaction time and accuracy, at either level of task difficulty. Interestingly, participants' self-rated perceived performance aligned with these findings and remained consistent across sound conditions. This suggests that participants were able to maintain their performance despite varying noise levels, possibly due to effective cognitive strategies or a level of task engagement that counteracted the potential disruptive effects of the noise.

One possible strategy may have been cognitive reframing, where participants abstracted the sound of the drone from its potentially distracting or negative connotations, effectively minimizing its impact. For instance, they might have mentally reduced the drone's sound to a neutral auditory stimulus, rather than focusing on its source or meaning. This aligns with the discussion in 6.5.4 "Beyond Acoustic," where the transition from perceiving the drone as an alerting signal to a mere background noise might have helped in maintaining focus. Another possibility is that the tasks themselves, particularly the 3-back task, were sufficiently engaging to foster a deep level of concentration, which served as a buffer against the drone noise. This effect is consistent with what we discussed in subsection 5.5.3, where goal-oriented behaviors may lead to attentional tunneling—filtering out irrelevant environmental stimuli, rendering them non-impactful. While attentional tunneling can enhance performance by focusing on relevant information [214], it also leads to a diminished awareness of other stimuli, effectively neutralizing potential distractions like drone noise. A result that aligns with this explanation is the observed interaction effect between the n-back condition and sound level on perceived mental workload (see Table 6.6). Specifically, sound level had a significant impact only during the 1-back condition, where participants reported that the task allowed for more mental wandering. This suggests that in less demanding tasks, where cognitive resources are not fully engaged, external stimuli like drone noise are more likely to intrude into the participants' awareness, increasing perceived mental workload. In contrast, during more demanding tasks like the 3-back, the cognitive load required to maintain performance may have effectively blocked out these distractions, resulting in a consistent performance despite varying noise levels.

However, it is also important to consider the duration of exposure to drone noise. Some participants reported becoming accustomed to the drone's sound over time, which suggests a possible habituation effect. Yet, this adaptation might come at a cognitive cost. The concentration required to filter out the noise may become more fragile as time progresses, potentially leading to mental fatigue. Indeed, several participants mentioned that their focus occasionally broke, resulting in the drone sound becoming very disruptive. This highlights a potential risk that prolonged exposure might eventually overwhelm the cognitive strategies used to manage the noise, particularly in longer or more demanding tasks.

While the impact of drone noise on task performance warrants further research—particularly to clarify the mechanisms that led to our findings and the role of exposure duration—our study did reveal a significant detrimental impact of drone noise on the subjective experience of task performance, as detailed below.

Subjective Experience

Although we did not observe significant differences in objective performance across varying drone noise levels, this does not necessarily imply that the sound had no impact. Participant feedback revealed that many found the drone's noise particularly distracting, which reduced their ability to focus and made the task more challenging—especially the 3-back task, which required higher concentration and mental resources. Our findings showed that varying sound levels significantly influenced participants' perceptions of pressure, effort, frustration, and physical workload during the tasks.

Interestingly, the low sound level consistently differed from both the medium and high sound levels, which were not significantly different from each other in these subjective measures. This pattern suggests the existence of a threshold effect: below a certain noise level, the detrimental impact of the drone's sound on the subjective experience is markedly reduced. However, once this threshold is surpassed, additional increases in noise intensity do not substantially worsen the subjective experience. This threshold may represent a point where the sound becomes sufficiently perceptible to disrupt cognitive processes and emotional states, but beyond this point, the human response system may have already maximized its adaptation or stress response, leading to a plateau in perceived disruption.

These findings underscore the importance of considering not just measurable performance outcomes like reaction times and accuracy, but also the qualitative aspects of user experience when evaluating the impact of environmental factors such as drone noise. Even if performance metrics remain stable, the impoverishment of the user experience—marked by increased mental strain, frustration, and physical discomfort associated with higher noise levels—could have long-term consequences. These include decreased well-being [151], reduced task engagement over time, and the reinforcement of a negative perception of drones.

6.5.3 Personal Experiences

Sound perception is a universal experience, yet it is uniquely shaped by individual differences. Recently, Lotinga et al. [242] highlighted a significant gap in psychoacoustic research on drones, pointing out the lack of consideration for personal characteristics such as "sensitivity to noise" and how these might influence subjective responses to sound exposure. Despite the recognized potential of these factors, they remain underexplored in the current literature. Our work directly addresses this gap by examining the relationship between individual noise sensitivity and perceptions of drone sound across different sound levels and task-related mental workloads. In our study, we observed a positive monotonic relationship between noise sensitivity and perceptions of the drone's sound—specifically loudness and annoyance—at moderate sound levels during the more demanding 3-back task. Additionally, noise sensitivity was positively correlated with participants' awareness of the drone under these same conditions. One possible explanation for these findings is a combination of limited cognitive resources and varying intensity thresholds for processing external stimuli.

Limited Resources and Intensity Threshold Kahneman's capacity theory of attention [195] suggests that cognitive resources are finite and that demanding tasks require a greater allocation of these resources [244]. The 3-back task, known for its cognitive complexity, likely left participants with fewer resources to process external stimuli such as the drone's sound, leading them to filter out the noise to focus on the task. This aligns with participant feedback indicating that the drone's noise was particularly distracting during the 3-back task, which required more concentration and mental resources.

Within the context of performing the 3-back task and the consequent limitation of cognitive resources, the ability to ignore the drone's sound was influenced by both the intensity of the noise and individual noise sensitivity. At the lowest sound level, most participants were able to disregard the drone's noise, leaving little room for individual sensitivities to manifest, except perhaps for those who were extremely sensitive. At moderate sound levels, individual differences in noise sensitivity became more apparent, with some participants able to filter out the noise while others could not—this variance likely contributed to the significant positive relationship between noise sensitivity and sound perception observed in our study. However, at the highest sound level, the drone's noise was so intrusive that most participants struggled to ignore it, regardless of their individual sensitivities, except perhaps for those who were exceptionally insensitive. This reduced the influence of individual sensitivities at both extremes of sound intensity. It aligns with prior research indicating that the level of perceptual load can predict whether individual differences in distractability will be found [134].

This finding is particularly important as it highlights a target for optimizing drone stimuli in real-world settings. Since drones will be deployed in environments with diverse individuals, each with unique profiles and sensitivities, it is crucial that their sound is not disruptive to some while manageable for others. Therefore, we should aim to achieve conditions similar to the low sound level observed in our study, where the noise was generally manageable regardless of individual sensitivity. Moreover, this result underscores that while individual characteristics may not always influence sound perception in less demanding contexts—such as during the 1-back task in our study—they can become significantly influential in more challenging situations, as observed in the cognitively demanding 3-back task. Therefore, drones should be context-aware and adapt their design and behavior accordingly. For example, in workspaces where individuals may be focused on complex tasks, drones could adopt a more "discrete" behavioral profile—such as operating at lower speeds, minimizing noise, and staying out of sight—to reduce potential distractions. Our work enhance our understanding of how personal characteristics such as "sensitivity to noise" might influence subjective responses to drone sound exposure, filling a gap in the existing literature on the subject [242].

Limitations of the Likert Scale While we might anticipate a correlation between noise sensitivity and annoyance regardless of task difficulty or sound intensity—particularly in conditions where attention to the sound stimuli remains consistent, such as in the 1-back task—the lack of significant correlations in some scenarios may stem from the limitations of our measurement approach. While Likert scales are a common tool in psychoacoustic research, they may not be sensitive enough to capture subtle variations in individual perceptions. For instance, when participants rate a stimulus as "moderately annoying," this label might obscure significant differences in how intensely individuals experience that level of annoyance. The term "moderate" could span a wide range of personal experiences, leading to an averaging effect that masks individual differences. Although our use of Likert scales aligns with established research practices, these scales might lack the precision needed to detect the nuanced variability in how drone sounds are perceived across different contexts and among individuals with varying noise sensitivities. This limitation underscores the need for more refined measurement techniques that can better capture the complexity and individuality of sound perception. Exploring alternative methods, such as continuous scales, more detailed qualitative assessments, or physiological measures, could provide deeper insights into the variability of subjective responses to drone noise.

Reaction Time as an objective measures In our study, we anticipated that higher negative attitudes towards drones and greater noise sensitivity might lead to increased stress and cognitive load, which could be reflected in subjective arousal measures. However, these effects may not have been fully captured by the Likert scale measures. An intriguing finding is that we consistently observed correlations between negative attitudes towards drones, noise sensitivity, and slower reaction times across conditions. This supports the notion that participants with higher negative attitudes or greater noise sensitivity might experience greater cognitive load or stress, leading to increased reaction times. Reaction times, being an objective measure, may offer a more accurate indication of underlying cognitive and emotional states compared to Likert scales, which might not detect subtle variations in cognitive load or stress.

However, it is important to note that correlation does not imply causation. While our results suggest a relationship between noise sensitivity, negative attitudes, and reaction times, they do not establish a direct causal link. Future research should further investigate this relationship to more definitively determine how these factors interact and influence cognitive performance.

6.5.4 Beyond Acoustics

While psychoacoustic research on drone sounds has extensively examined the impact of acoustic features on perception in controlled environments—often without the presence of an actual drone—this approach may overlook critical aspects that HDI research needs to address. Lotinga et al. [242] emphasized that most psychoacoustic drone studies have elicited noise annoyance ratings from participants without contextualizing their responses. In carefully controlled conditions, this type of response may represent a form of 'psychoacoustic annoyance,' which is related to sound qualities but largely devoid of judgment framing and emotional connotations.

A Conveyor of Meaning

The sound of a drone is not merely an auditory stimulus; when placed in a more realistic setting, the drone's sound transitions from a simple noise to a meaningful cue, intertwined with other dimensions and potential concerns. Previous work has shown that while the drone's sound was perceived as annoying, it also served a practical purpose—helping participants locate the drone while navigating around it. This insight emerged only when participants were placed in a realistic interaction context (see chapter 5). The utility of sound as a localization cue has been explored in Human-Robot Interaction research [81], and it is known that moving sounds within peripersonal space can modulate the motor system, responding to the representation of an approaching entity via this sensory channel [127].

Participants in our current study echoed these findings. One participant reported moving away from the drone to detach its sound from its physical presence, making it easier to process. This aligns with another participant's observation that perceiving the drone's sound as mere noise, without the associated physical presence, reduced the perceived threat.

This phenomenon raises an interesting question: How does the perception of drone sound differ when experienced in a collocated context versus through headphones without direct visual contact? Comparing these two conditions could reveal how they differ in terms of perception and the information that may be lost or gained with each method. Such research could provide valuable insights into how these methods might complement each other, enhancing our understanding of the full scope of human-drone sound interaction. Previous studies have shown that moving sounds within peripersonal space can activate the motor system, suggesting that the illusion of presence through the auditory channel is possible [127]. However, this experience might be limited compared to real-world exposure.

This also raises questions about the validity of virtual approaches to studying the sound dimension of human-drone interaction, as such methods may foster a psychological detachment between the auditory stimuli and the virtual drone being presented. An in-depth study could explore this issue, aiming to understand when sound is considered an informational cue versus a mere auditory stimulus without associated contextual relevance. Is the annoyance that arises from an unpleasant sound stimulus (psychoacoustic annoyance) the same as the one that signals a drone is approaching and requires attention (informational annoyance)? Investigating this distinction could deepen our understanding of the multifaceted role of sound in human-drone interaction.

An Emotional Sound

Another crucial aspect of drone sound that should not be overlooked is its emotional connotations. Research has demonstrated that emotionally charged sounds elicit stronger sympathetic responses and impair cognitive performance more than neutral sounds [25]. Negative sounds are generally perceived as more annoying and unpleasant, often triggering heightened alertness and a sense of danger, which can lead to increased physiological arousal [25, 219, 347]. In our previous research, participants frequently compared the drone's sound to that of insects. Although I personally view insects positively, this comparison was not well-received by participants and may have heightened the perceived threat of the drone [59].

While it might have been assumed that the drone's sound would consistently be perceived negatively, our findings suggest a more nuanced perspective. Although acoustic features, particularly loudness, primarily influenced sound perception, interviews revealed that the emotional connotations of the sound could shift with its intensity. For instance, lower sound levels were often compared to insects (e.g., flies), while louder sounds were likened to more familiar and benign sources, such as ceiling fans. This shift in association may have unlocked some unexpected positive effects of louder sound conditions, including increased focus (similar to the effects of white noise) and a potentially relaxing effect.

Despite the generally detrimental impact of increased loudness, which outweighed the potential benefits of this phenomenon, the shift in connotation—from an insect-like sound to a ceiling fan—suggests a potential pathway for improving drone sound perception. Recent work by Wang et al. [370] supports this notion by exploring how overlaying natural sounds onto operating drones can manipulate the emotional valence of drone noise. Their study illustrates the potential for enhancing people's perception of drone sounds through emotional valence manipulation, although it also highlights the challenge of addressing negative acoustic features, especially when drones operate at close distances.

Future research could further explore the role of emotional valence manipulation in conjunction with acoustic features to better understand and improve drone sound perception. Notably, while we struggle to envision drones sounding nice, one might imagine that in the future the sound drone makes would be generally positively perceived, inducing positively valenced arousal that migh lead to approach behaviours.

6.5.5 Arousal and Distance Adjustment

Arousal regulation theory posits that individuals strive to maintain an optimal level of arousal, where insufficient arousal leads to disengagement, and excessive arousal results in overstimulation and stress [48]. Spatial adjustment, such as moving closer to or further from a source of stimulation, is a common strategy to regulate arousal [11, 122, 282], making it a potentially significant factor in human-drone interactions (HDI). Our study aimed to uncover how this proxemic behavior functions in an HDI context.

We hypothesized that varying the drone's sound levels would create different levels of sensory stimulation and associated arousal, leading to distinct spatial adjustments as participants sought to regulate their arousal. This hypothesis was validated, with drone noise significantly impacting both subjective arousal and maintained distance (see Figure 6.7), both increasing as sound intensity rose.

We also anticipated that the task difficulty, which influences initial arousal levels, would similarly affect how participants adjusted their distance from the drone. While task conditions did impact perceived arousal, this did not translate into statistically significant differences in maintained distances. Participants' feedback, however, revealed a more complex relationship between task-induced arousal and spatial adjustment than we initially envisioned, challenging two of our assumptions: first, that spatial adjustment would be the primary strategy for regulating arousal, and second, that the arousal induced by drone noise is uniformly negatively valenced.

Some participants adjusted their distance from the drone as anticipated, recognizing that moving away effectively reduced sensory stimulation. Crucially, it was not just the noise but the combination of the drone's sound and the task's demands that triggered this response, as the combined pressure led to a sense of overwhelm. For example, one participant explained that distancing themselves from the noise allowed them to clear their mind and improve their performance, underscoring how the task's added strain made the noise particularly disruptive. This finding supports our hypothesis that spatial adjustment can serve as a strategy for arousal regulation around drones and highlights how contextual factors, such as task demands, can significantly influence proxemic behavior driven by arousal regulation.

In contrast, other participants did not use spatial distance to manage arousal. Instead, they employed cognitive strategies [48], such as increased focus, to cope with the noise. By applying the framework developed in Chapter 5 on goal-oriented behaviors and their influence on proxemic interactions, we could have predicted this outcome. While drone noise can be perceived as an obstacle to task performance, how individuals choose to address this obstacle varies. Some participants chose to mentally block out the noise rather than move away from it. As discussed in Chapter 5, even tasks that seem unrelated to proxemics can influence spatial behavior by altering participants' perception of their environment, including phenomena like tunnel vision—where focused attention narrows the perceptual field, reducing the salience of peripheral distractions such as drone noise.

Interestingly, some participants exhibited approach behaviors, using the drone's sound to their advantage. This finding challenges the assumption that drone noise is always a nuisance, suggesting it can have beneficial effects in specific contexts. In this case, the drone's sound acted as a barrier to other external distractions, allowing participants to concentrate solely on the task and the noise, thereby enhancing their focus. Rather than moving away from the drone, these participants sought an optimal sound intensity level that would mask other potential distractions, effectively creating a "sound bubble" that facilitated concentration. This adjustment was still influenced by sound levels, with the optimal intensity reached at greater distances as the noise increased. For more demanding tasks like the 3-back, this sound bubble became more appealing, leading to approach behaviors. The task's difficulty and the perceived usefulness of the drone's sound shifted the arousal valence from negative to positive, supporting the arousal regulation theory that positive arousal can lead to approach behaviors.

Ultimately, these varied behaviors may have contributed to the absence of statistically significant results, as no single proxemic response dominated across all task conditions. However, this diversity in responses validates the hypothesis that distance adjustment can regulate arousal stemming from drones. The significant positive correlation between subjective arousal and maintained distance further supports this interpretation (see Figure 6.8).

Our findings also raise concerns about deploying drones in environments where individuals are already aroused, such as during demanding tasks, as this can lead to feelings of overwhelm. However, they also highlight opportunities to use drones to influence proxemics by leveraging this arousal-driven mechanism to trigger approach behaviors. By modulating arousal—whether positively or negatively valenced—drones could potentially guide spatial interactions. Nevertheless, individual differences play a significant role, making it challenging to develop a one-size-fits-all approach.

6.6 Chapter Conclusion

This chapter has explored the intricate relationship between arousal regulation and proxemic behavior in human-drone interactions (HDI), specifically focusing on how varying drone sound levels and task difficulty affect spatial adjustments. We also aimed to fill significant gaps in the literature concerning drone sound perception, which often neglects the influence of contextual and personal factors, as well as behavioral responses and task performance.

Our findings affirm that spatial adjustments in response to drones are a key strategy for arousal regulation. Drones can induce various types of arousal, from annoyance due to auditory stimuli, as observed in this study, to perceived physical threats, as discussed in previous chapters. The extent of these arousal responses, influenced by context and individual characteristics, often dictates spatial adjustments, shaping proxemic behavior.

In addition to addressing proxemics, this study contributes to the literature on drone sound perception by examining how contextual factors (e.g., task nature) and individual characteristics (e.g., noise sensitivity) impact the perception and effects of drone noise. We also evaluated how drone sound exposure affects both objective and subjective task performance, highlighting the complex nature of drone sound design.

However, this study has limitations. The reliance on subjective Likert scales, while informative, may not fully capture the complexity of participants' experiences or the nuanced interplay between arousal and proxemics. Future research should incorporate objective measures and qualitative methods to achieve a more comprehensive understanding.

Transition to Next Chapter Building on these insights, the next chapter integrates the various mechanisms underlying proxemic behavior into a unified model of human spatial dynamics with external entities, including during human–drone interactions. By synthesizing findings on arousal regulation, goal-oriented behaviors, defensive responses, and communicative functions, this model provides a holistic framework that captures the complex interplay of these factors. It offers a comprehensive perspective on the diverse influences shaping spatial interactions with drones and other external entities.

6.6.1 **Research Question 1.4 –** What is the role of the Arousal Regulation Proxemic Function in HDI?

The Role of Arousal Regulation Proxemic Function

Arousal regulation refers to the management of one's physiological and psychological state in response to environmental stimuli [48]. In the context of proxemics, individuals strategically adjust their spatial behavior to modulate arousal: heightened arousal from stress or discomfort typically leads to increased distance from the source [122], while positively valenced arousal, such as excitement or interest, encourages approach behaviors [282].

This proxemic function has been considered a driving mechanism influencing people's spatial behaviors around drones, particularly given the high potential for drones to elicit significant arousal. This arousal can stem from a variety of sources—ranging from sensory stimulation to perceived threats, or even positive excitement due to curiosity about new technology.

Reflecting on our previous works, evidence of arousal-regulation-driven proxemics has emerged consistently. In our first study [57,58], presented in Chapter 3, we observed participants getting unusually close to a virtual drone, raising concerns about the validity of our virtual approach. This behavior, however, could be interpreted as being driven by positive arousal, where curiosity and excitement prompted some individuals to approach the drone for closer observation (see section 3.2.5). Later, while exploring goal-oriented behaviors in Chapter 5, We observed that participants' spatial behavior could be interpreted as a form of arousal regulation. Faced with the drone as a potential threat, participants reported lacking the resources to navigate close to it while effectively performing their task, leading them to take larger deviations and increase their speed to balance the situation (see subsection 5.5.2).

In this chapter, we specifically investigated the drone's sound, a critical design aspect identified as a significant source of arousal. Our findings demonstrated that subjective arousal increased with sound intensity, correlating with perceived annoyance, suggesting a negative arousal response. This was accompanied by maintained distances, indicating that spatial adjustments were made to mitigate this negative arousal. However, as observed in the goal-oriented chapter, we noted a diverse range of behaviors in response to the task's demands, which varied between low (1-back) and high (3-back). For some, observed behaviors and reported motivations aligned with the arousal regulation proxemic function, with the more demanding task narrowing the range of drone-related stimulation that participants could tolerate. This led them to maintain greater distance compared to the less demanding task, illustrating how contextual factors can shape the arousal acceptance threshold. For others, the shift in task demands significantly influenced their overall experience, including alterations in sensory perception and the adoption of arousal regulation strategies that did not rely on spatial adjustments, such as increased focus and filtering out the drone's sound. Interestingly, these behaviors are consistent with patterns observed in our previous studies involving different human-drone interaction scenarios, suggesting that while a variety of responses may occur, they tend to follow a coherent and predictable set of strategies.

Even within controlled settings, predicting the specific strategies individuals will adopt when faced with arousal-inducing stimuli, such as drone noise, remains challenging, particularly due to the influence of personal factors. This complexity underscores the multifaceted nature of proxemics in human-drone interactions.

To aid researchers in exploring the arousal regulation facet of human-drone proxemics in their studies, we recommend the following approach:

1. **Identify Potential Arousal Sources:** Catalog the possible sources of arousal linked

to the drone, such as perceived threat, auditory stimuli, or curiosity, along with factors stemming from the interaction context, such as environmental stimuli or task demands.

2. **Consider Perceptual Influences:** Reflect on how participants perceive the situation from a sensory perspective, recognizing that this perception can be influenced by contextual elements like the task at hand. Since perception is the initial step in many cognitive and behavioral processes, understanding how it varies among individuals is crucial for interpreting proxemic behaviors.

3. **Consider Personal Factors:** Reflect on personal characteristics that may influence individual responses to these arousal sources, and if feasible, incorporate measures to assess them (e.g., using scales like noise sensitivity when investigating drone sound).

4. **Evaluate Interaction of Arousal Sources:** Assess how these arousal sources might interact and potentially compound one another, which could lead to arousal regulation responses. This step involves considering the cumulative impact of multiple stimuli on the individual.

5. **Determine Arousal Regulation Strategies:** Consider whether spatial adaptation (e.g., adjusting distance) [11, 122, 282] or alternative strategies, such as cognitive coping mechanisms [48, 133], are likely to be employed by individuals to manage their arousal. Understanding the likely strategies can inform the interpretation of experimental results.

Ultimately, arousal regulation represents a higher-level proxemic function that intersects with goal-oriented, defensive, and communicative functions. Frameworks such as cognitive appraisal theories [48, 133] and the situational awareness model [114, 115], discussed in chapter 4 (see subsection 4.6.1), as well as our framework for goal-oriented behaviors in chapter 5 (see subsection 5.6.1), are also highly relevant to understanding arousal regulation. This is particularly true in the context explored here, where individuals were engaged in task performance.

Arousal regulation offers a comprehensive framework for understanding the multiple influences and forces shaping proxemic behavior. It provides a broader perspective on how immediate sensory stimuli, as well as complex emotional and cognitive responses, interact to affect spatial behavior.

However, applying arousal regulation in practice can be challenging due to the wide range of potential arousal sources and the complexity of measuring both these sources and individuals' arousal responses. This diversity complicates the task of isolating and measuring specific arousal sources, making it difficult to directly link them to proxemic behavior. Thus, while arousal regulation provides a broad perspective, its practical application may be limited.

6.6.2 Contribution to Research Question 2 – How best to use VR to study human-drone proxemics?

Harnessing VR's Technological Progresses

Throughout this thesis, we have observed the rapid evolution of VR technology. Initially, VR headsets like the HTC Vive were tethered to computers by cumbersome cables, which limited movement and complicated the observation of natural proxemic behaviors. The advent of Meta's Quest series, standalone headsets free from cables, marked a significant leap forward. This advancement enabled us to design environments where participants could move freely and interact more naturally. However, this progress introduced new challenges, such as accurately assessing distance perception and situational context. To address these, we developed a generic protocol for our studies (see subsection 4.6.1), which involved replicating the experimental room. Although this setup was initially labor-intensive, it provided a reusable framework, albeit with the limitation of confining the experiment to a fixed location.

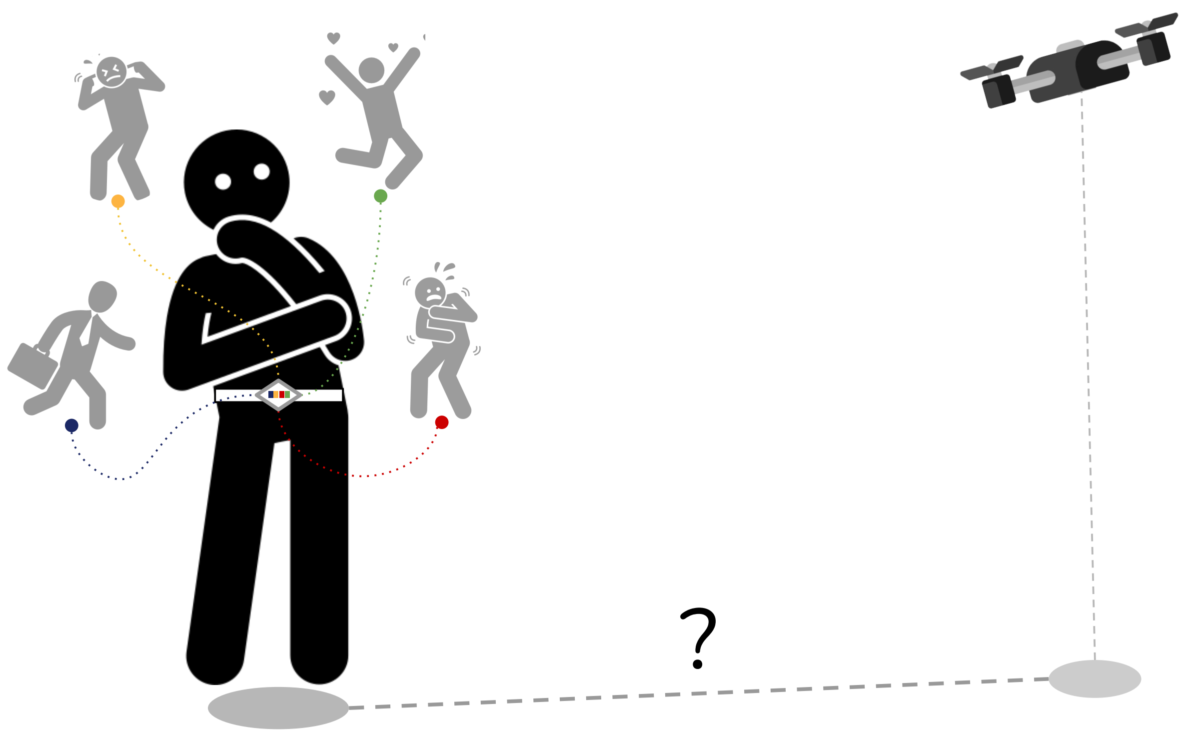
From Virtual to Mixed Reality The recent release of the Meta Quest 3, featuring advanced passthrough technology, has further enhanced our experimental capabilities. This technology allows us to create near-augmented reality experiences while maintaining the simplicity and benefits of VR implementations, offering new possibilities for experimental design and simplifying our existing approach. The study presented in this chapter illustrate the first use of this approach to investigate human–drone proxemics. The protocols developed in Chapter 4, which enhance ecological validity and support external evaluation of virtual human-drone interactions (HDI), have been effectively applied to this new context (see subsection 6.3.1). This advancement has addressed previous concerns related to fully virtual environments, such as issues with distance perception and embodiment.

An additional practical benefit of this transition is the improved communication between participants and experimenters. In fully immersive VR, participants are isolated from the real world, complicating interactions such as providing instructions or answering questions. The mixed reality approach allows participants to see and hear the experimenter as they would in the real world, facilitating clearer communication. This enhancement has made it easier to explain the study's procedures and interact with participants, thereby improving the overall experimental experience.

In conclusion, the rapid advancements in VR technology underscore its transformative potential for research. By leveraging these innovations, researchers can achieve greater ecological validity, refine experimental designs, and explore complex interactions in increasingly realistic and immersive environments. Embracing these advancements will likely drive future research forward, providing deeper insights into human behaviors and interactions with autonomous drones.

Chapter 7

A Unified Model of Proxemics: The Dynamics of Human Spatial Relationships with External Entities



Reader's Note: Congratulations on reaching this point in the thesis! By now, you should have a deeper understanding of the various factors influencing proxemic behavior around drones. This chapter aims to integrate these insights into a cohesive model, connecting findings from previous chapters and offering a comprehensive view of the subject.

If you started with this section, you've focused on the core of the research. For a more complete understanding, we recommend reviewing the summary of key insights on proxemics discussed in the literature (see section 2.2.1). This summary provides the foundational knowledge for the model presented and offers an overview of the proxemic functions explored throughout the thesis.

7.1 Chapter Introduction

7.1.1 Motivation

Throughout Chapters 3 to 6, we explored human–drone proxemics through specific lenses, each providing valuable insights into the distinct mechanisms driving spatial behavior in Human-Drone Interaction (HDI). These focused approaches helped clarify the role of different proxemic functions in HDI but also imposed limitations by examining them in isolation. Leichtman et al. [227] advise researchers to employ proxemic frameworks suited to their specific study, which initially guided our effort to verify the relevance of proxemic functions within HDI and understand their roles. Having accomplished this, the thesis could have concluded, claiming, "This is human-drone proxemics." Yet, we couldn't ignore the greater complexity of proxemic behaviors that emerged from our work.

For example, focusing solely on one function, such as the defensive function, may obscure a broader range of behaviors driven by other mechanisms, leading to misinterpretations. While, in some cases, individuals use space as a safety margin to ensure their physical integrity, this is only one lens. An individual might get close to a drone not because they assessed it as non-threatening but simply because they were focused on their task and failed to notice it—highlighting the fundamental role of sensory perception and goal-oriented behavior. Conversely, they might increase their distance not because they perceive the drone as dangerous but because the cognitive load associated with its presence at close range exceeds their available resources. Both phenomena were observed in our studies (see chapter 5), yet they are not unique to human–drone interactions. Similar spatial behaviors occur in interactions with other external entities, such as humans, robots or even animals.

A function-specific approach often overlooks the intricate interplay between various proxemic functions and lacks the necessary detail to capture the full range of observed behaviors. This approach also introduces ambiguity, as proxemic behavior is dynamic, context-dependent, and deeply influenced by an individual's perception and interpretation of sensory inputs (see section 2.2.1).

Given these insights, we propose a more comprehensive framework rooted in core proxemic principles (see section 2.2.1), starting at the foundation: sensory perception. Beginning with how individuals process external entities outputs (see section 7.2), this sensory processing perspective unravels how different levels of perception—ranging from basic awareness to the projection of future states—give rise to overlapping approach and avoidance forces. These forces, which we term proxemic potentials, are linked to proxemic functions and ultimately balance themselves to produce a singular proxemic behavior. While this model was developed from studies in HDI, its principles extend beyond drones and offer a generalized framework applicable to other entities, including humans, and ground robots.

7.1.2 Chapter Structure

This chapter opens with a sensory-based perspective on proxemics, addressing a key gap in understanding how people regulate interpersonal space with external entities, including social drones. By incorporating sensory processing into the study of proxemics, we aim to clarify the origins of various proxemic behaviors and the factors that influence them. This perspective helps us connect the different proxemic functions examined in earlier chapters, showing how they stem from sensory input and interact with one another. The following section builds on this sensory foundation by presenting our conceptualization of human proxemic behavior in response to external entities. This framework emerges from the initial stages of sensory information processing and situational assessment, integrating multiple layers of proxemic potentials. These layers correspond to various functions—such as defense, arousal regulation, performance optimization, and social communication—that shape how individuals respond to their surroundings. While we illustrate this framework using drones as a case study, the model is designed to be adaptable to other entities, such as humanoid robots or animals. The chapter concludes with a summary of the core principles behind our framework, highlighting its potential for future research and applications, as well as a discussion of limitations and opportunities for further development.

7.2 A Sensory Perspective

In everyday life, we are immersed in a nearly infinite array of sensory inputs, with external entities such as drones, robots, or even other humans forming just one part of this sensory landscape. Only a small fraction of these inputs are actively perceived, while the rest are automatically filtered out [62] or minimized [353]. Among those that reach conscious awareness, some are further processed to construct an understanding of our surroundings and the entities within them. This sensory foundation informs various cognitive mechanisms—many of them unconscious—that drive behaviors such as cognitive appraisal [48, 133], defensive responses [44], and

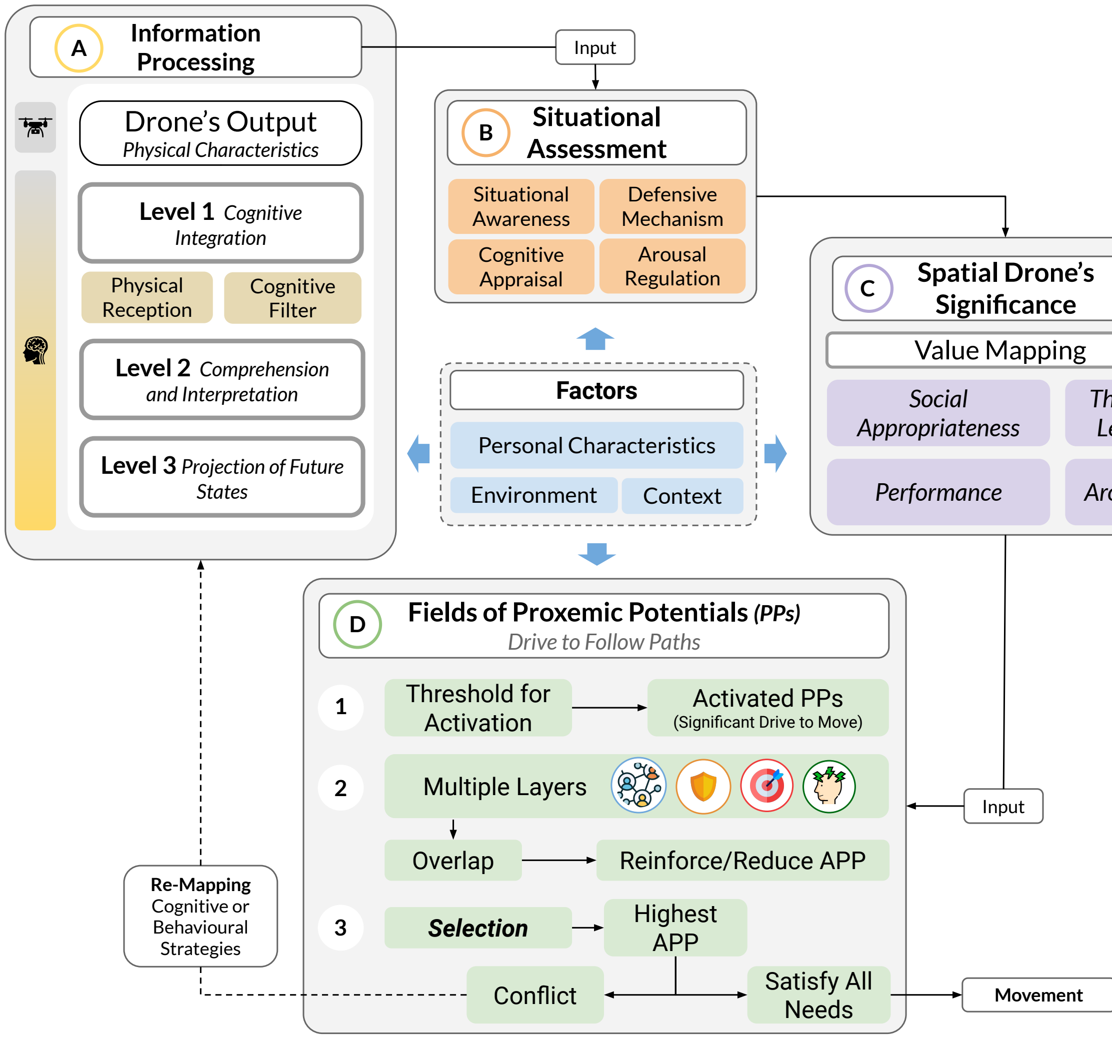


Figure 7.1: Schematic representation of our conceptualization of human proxemics with external entities, illustrated through a drone encounter.**A)** Sensory cues from the drone are perceived and processed by the individual. **B)** This information feeds into the individual's ongoing situational assessment, where the drone's presence is evaluated in context. **C)** If the drone is deemed significant in terms of factors like social appropriateness, threat level, performance, or arousal, these values are mapped in the individual's surrounding space relative to the drone's position. **D)** Based on this value mapping and their current position, the individual may be driven toward different paths, with overlapping proxemic motivations interacting, as outlined in section 7.3.3. This dynamic may lead to movement or re-mapping strategies to resolve conflicts between competing forces.

situational awareness [114, 115]. Ultimately, as Hall noted, perceiving and interpreting sensory inputs is the first step in the proxemic process [163] (see section 2.2.1).

In this section, we outline four levels of cognitive perception that shape how individuals process sensory inputs and respond to external stimuli. These levels describe how raw sensory information becomes meaningful, influences situational understanding, and ultimately guides behavior. While the framework applies broadly, we illustrate it here with an example of a drone in a library setting:

- **Level 1: Cognitive Integration** At this stage, sensory inputs enter conscious awareness, forming the foundation for further cognitive processing. At this stage, sensory inputs enter conscious awareness, forming the foundation for further cognitive processing. For instance, someone deeply focused on reading in a quiet library may not immediately register a background noise. If the sound persists—such as a faint buzzing—it eventually breaks through their attention, prompting them to shift focus. Without further analysis, they might react automatically, moving to a quieter area simply because "something was distracting them," even if they haven't consciously identified the source. Alternatively, another person might experience the buzzing as a steady, predictable noise that helps mask other distractions, making it easier for them to concentrate. In this case, rather than prompting avoidance, the sensory stimulus becomes an aid to focus, demonstrating how cognitive integration shapes different behavioral outcomes.

- **Level 2.1: Comprehension** Once awareness is established, individuals begin assigning basic, abstract meaning to the stimulus. They may recognize that the sound originates from a moving object and infer its approximate location. When the available information is insufficient, they might engage in exploratory behaviors—such as glancing around or repositioning themselves—to clarify the nature of the stimulus and determine whether it is relevant to them.

- **Level 2.2: Interpretation & Association** Beyond basic comprehension, people integrate the stimulus into their personal experience and cognitive models, leading to varied responses. Upon identifying a drone, one person might view it as an automated assistant performing a task, such as sorting books, which allows them to easily dismiss it as non-disruptive. In contrast, another person might associate its buzzing with an insect, subtly influencing their perception and making it harder to mentally dismiss the drone. These differences illustrate how prior experiences, expectations, and situational context shape perception.

- **Level 3: Projection of Future State** Finally, individuals use the information gathered to anticipate future actions and adjust their behavior accordingly. After observing the drone's movement pattern, someone might predict that it will continue scanning the aisles and choose to relocate before it reaches their space. This predictive processing is a fundamental aspect of proxemic behavior, influencing how people position themselves not only in response to drones but to a variety of moving entities in shared environments.

Importantly, as noted by Mesulam et al. [254], connections between cognitive processes are reciprocal, allowing higher-level synaptic activity to exert a top-down influence on earlier stages of processing. Various factors—such as attentional focus, motivation, emotional states, working memory, novelty-seeking, and mental imagery—contribute to the creation of a subjective and highly edited version of the world [254]. Each individual's experience with a stimulus, such as a drone, can vary significantly, and the complexity of cognitive processing and interpretation will depend on the context and the individual's engagement with the stimulus.

While some individuals may remain at early stages of processing, failing to notice or meaningfully attend to the stimulus, others may engage briefly with it, gathering basic information relevant to their current activity without deeper interpretation. In contrast, some may progress to more complex cognitive stages, involving the creation of mental models and the assignment of meaning or intentions to the stimulus. For example, one person may view the drone as a harmless, task-oriented object, while another may interpret it as intrusive or even threatening. These variations in perception arise from the diverse ways in which individuals process and interact with their environments. Such cognitive variability underscores the importance of a flexible framework that accommodates the multi-layered nature of perception, rather than relying on a one-size-fits-all approach to proxemic behavior and Human–Drone Interactions.

7.2.1 Level 1 – Cognitive Integration

In this section, we present a box model (see Figure 7.2) that illustrates the flow of sensory input from an entity's output to the cognitive integration process—a crucial foundation for higher-level cognitive activities. This framework draws from well-established theories, including Kahneman's Theory of Attention and Effort [195], Broadbent's Filter Theory [62], Treisman's Attenuation Theory [353], and recent neuropsychological insights [105,215,223,361]. The model Figure 7.2 shows how sensory information—whether from a drone or other external stimuli—enters the cognitive system and undergoes initial integration. This process is influenced by environmental, personal, and contextual factors, which may alter how the information is perceived. For example, individual differences in sensory reception can affect how we process external inputs, leading to variations in response to the same stimulus. The model also highlights the role of sensory overload, under-stimulation, or over-stimulation, which can occur prior to higher-level cognitive processing, influencing behaviors such as distance adjustments linked to arousal regulation [122]. Through examples from our own observations of human-drone interactions, we illustrate how these theories play out in real-world scenarios, showing how individuals perceive and react to drone stimuli based on their unique cognitive processing capabilities.

Entity's (Drone) Output While we use drones as a primary example, the same principles can be applied to any external entity in an individual's environment. The drone's output consists of measurable physical characteristics transmitted through multiple sensory channels. These include visual signals (such as lights, displays, and the drone's form), as well as auditory signals like sound [38]. Each modality—whether light intensity, resolution, size, color, or acoustic features—can be objectively described.

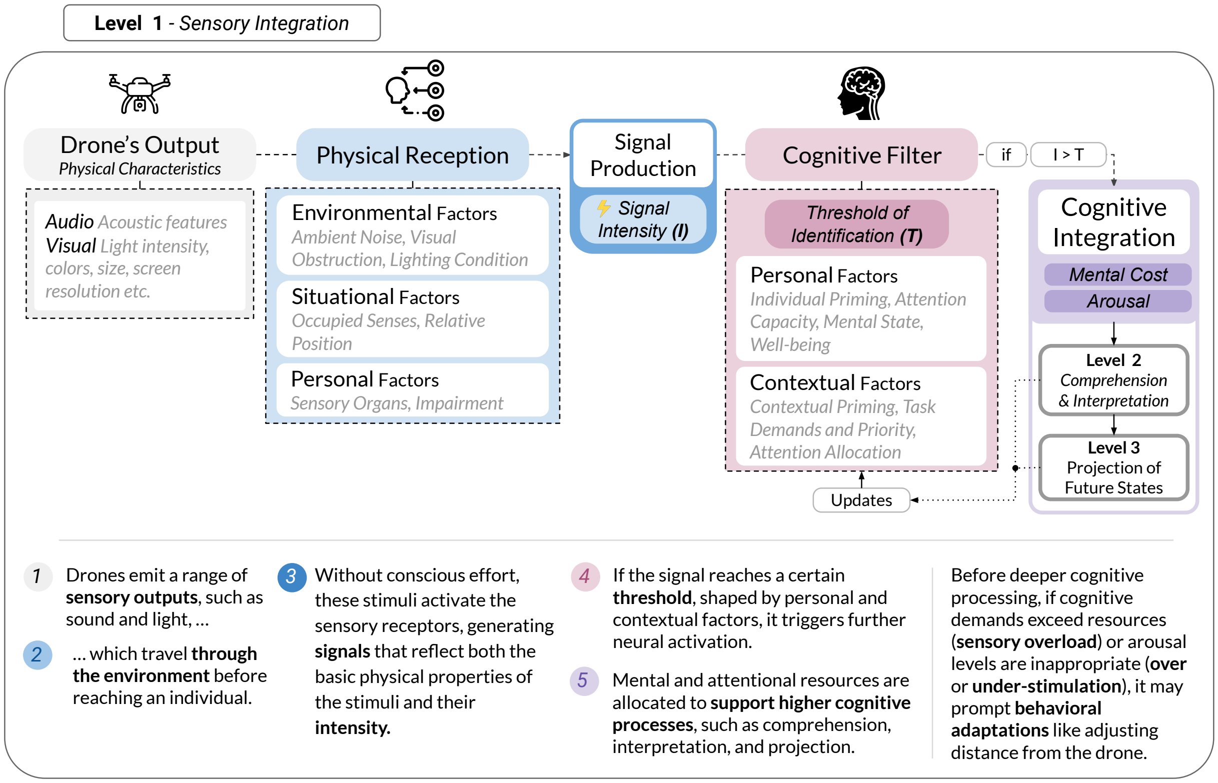


Figure 7.2: Schematic representation of the flow of sensory output from a drone, tracing the path from emission to cognitive integration. The diagram emphasizes how individual differences, environmental factors, and sensory overload can impact the early stages of perception, influencing subsequent behaviors such as distance adjustments for arousal regulation [122]).

Some drone outputs, like sound from propeller rotation and the shape of the drone, are unintended side effects of its design. Others, such as light signals and displays, are intentionally used for communication—conveying directionality [345], emotional expression [172], or initiating interaction [149]. These signals must reach the user's sensory receptors to be perceived and processed.

Physical Reception The second step in processing the drone's output is the physical reception of its signals, which is shaped by environmental, situational, and personal factors. These factors determine how well the emitted signals reach an individual's sensory organs.

- **Environmental factors** Environmental factors such as obstructions, ambient noise, and light conditions can affect how effectively the drone's signals are perceived. For example, walls or furniture can block visual and auditory signals, while high noise levels or poor lighting can reduce the clarity of sound and visual cues (e.g., light, displays).

- **Situational factors** further impact the physical reception of the drone's output. If a person is not looking in the direction of the drone or is engaged in another activity, such as listening to music, their ability to perceive the drone's signals may be diminished. Distance from the drone also affects reception; signals may weaken as the distance increases, leading to reduced sensory input.

- **Personal factors** also play a significant role in physical reception. The capabilities and sensitivities of an individual's sensory organs determine how well they can detect the drone's signals. Sensory impairments or differences, such as partial hearing loss or visual impairments, can further influence the effectiveness of signal reception.

The combination of these factors creates a unique sensory experience for each individual. This step highlights that the signal sent by the drone is not always the same as the signal received, with practical implications for designing communication cues that are both effective and accessible.

Signal Production Once the sensory receptors engage with the drone's output, neural signals are generated that encode the basic physical properties of the stimuli, such as its intensity. This process occurs unconsciously, with the neural signals being transmitted to the brain for further processing.

Cognitive Filter At this stage, attentional selection theories—such as Broadbent's Filter Theory [62], Treisman's Attenuation Theory [353], and Treisman and Gelade's Feature-Integration Theory [354]—are crucial. These theories describe an automatic filtering process that prevents unnecessary stimuli from being processed, optimizing the use of limited mental resources [195]. Stimuli that exceed a certain **threshold of significance** are processed at higher cognitive levels, while others are suppressed. This threshold is dynamically adjusted by both personal and contextual factors, guided by top-down processing feedback [254]. Signals that surpass the filter's threshold may evoke varying levels of arousal, require different amounts of attention, and induce different degrees of mental effort, depending on their intensity and relevance [195, 273].

Reynolds' Normalization Model of Attention [299] offers another perspective by illustrating the interaction between three fields: **stimulus, attention, and suppression**. This model visualizes how individuals uniquely perceive stimuli, akin to an image where the attention layer illuminates certain areas while the suppression layer darkens others, creating a dynamically contrasted and personalized mental representation of the external world [299]. This theory offers an intuitive understanding of how stimuli can be amplified or minimised.

The threshold for identification is influenced by several factors described below, which can be thought of as layers of attention and suppression that dynamically shape each individual's sensory experience. These factors, illustrated through examples from our studies, provide insight into how early-stage stimulus selection shapes perception and response to external stimuli—including drones—across various contexts.

Personal Factors In our exploration of human-drone proxemics across various interaction contexts, we have consistently observed striking diversity in individual behaviors and feedback, even within highly controlled experimental settings. While proxemic functions alone provide limited explanations for these differences, the underlying causes may be rooted in individual perceptual experiences. As Hall's ethnological observations suggest, people 'not only speak different languages but, what is possibly more important, inhabit different sensory worlds' [163]. By examining the factors that shape each individual's sensory world, we can gain deeper insight into the nuanced ways people navigate and interpret their spatial surroundings—not only in relation to drones but to any external entity within their environment.

- **Personal Experience:** Previous research suggests that the ability to inhibit distractors is influenced by prior experience with the stimuli [361]. Individuals generally react less strongly to familiar stimuli due to habituation, a process in which repeated exposure leads to a diminished response. For instance, frequent exposure to the sound of a particular drone may result in desensitization, requiring a stronger or more novel cue to capture attention. This effect was observed in our studies, where participants reported reduced sensitivity to the drone's sound over a 40-minute session (see chapter 6, subsection 6.4.4). Conversely, stimuli previously associated with high relevance or strong emotional responses tend to be more salient and are noticed more readily due to a lower threshold of significance. This is particularly relevant for the design of external entities, such as drones, as their sensory outputs often evoke associations with stimuli that people are conditioned to notice. For example, participants in our studies frequently described drone sounds as reminiscent of insects like mosquitoes or wasps, which are typically linked to danger. Such associations can amplify the salience of the drone's presence, making it more likely to attract attention. While this can be leveraged to enhance awareness, excessive salience may also lead to sensory overload or heightened alertness, potentially disrupting the user experience if not carefully managed [313].

- **Personal Expectations:** In any given context, individuals develop mental representations of expected sensory environments, making unexpected stimuli more noticeable and significant [137]. For example, in a library, people unconsciously filter out background sounds such as whispers, footsteps, or rustling pages, as these align with their expectations of a quiet space. However, the unexpected sound of a flying drone would immediately stand out due to its incongruence with the anticipated sensory experience.

  This expectation-driven filtering is shaped by personal experiences, mental models, and broader influences such as cultural norms and social contexts [163]. Research suggests that unexpected perceptual experiences are linked to stronger emotional arousal, particularly negative arousal, and can leave a lasting impact on first impressions [297]. This aligns with our observations (see chapter 3, subsection 3.2.6), where participants' expectations of the drone—formed by its initial social presentation—significantly influenced their experience. Many participants later noted that they focused more on the absence of anticipated social cues rather than the drone's actual behavior, which may have contributed to a more negative overall impression.

This highlights that while individuals may attend to an entity as a whole (e.g., a drone), their attentional filter selectively amplifies or suppresses specific features. This suggests that attentional manipulation through stimulus design and cognitive framing can guide focus toward desired elements (e.g., communication cues) while downplaying less favorable ones (e.g., potentially threatening elements like propellers), as discussed in chapter 4 and section 4.4.3.

- **Individual's Sensitivity**: Sensory sensitivity varies across individuals, affecting how effectively they can filter out stimuli from different sensory channels. For example, those with heightened auditory sensitivity may find it challenging to ignore background noise that others easily suppress. In our study (see chapter 6), noise sensitivity was positively correlated with both the perceived loudness of the drone and participants' awareness of its presence under specific conditions. This suggests that individuals with greater auditory sensitivity are more prone to attentional disruption from drone sounds. Such differences highlight the importance of accounting for sensory sensitivity in stimulus design, as it can significantly impact user experience and interaction.

- **Attention Capacity:** Attention capacity varies significantly among individuals, particularly in neurodivergent populations where attentional demands can easily overwhelm cognitive resources [313]. In the second study of chapter 3, a participant reported difficulties processing instructions and later disclosed that they were neurodivergent, which led to their exclusion due to recruitment criteria. However, their participation proved insightful. When asked about the expression displayed on the drone's digital face, they were unable to recall or notice it, explaining that they had not attended to it. Their cognitive resources were fully occupied by the task at hand, leaving insufficient capacity to process the drone's digital face, even though it was designed to be visually salient and that other participants had no issues. This observation highlights how an individual's limited attentional capacity can restrict their ability to process secondary stimuli, even when those stimuli are meant to stand out. Failing to consider such variations can inadvertently turn cognitive or sensory differences into functional disabilities. While this research focuses on autonomous drones, other works have begun exploring ways to adapt drone interaction for pilots with disabilities [143], aligning with the inclusive technology approach. Such initiatives emphasize the need to design technology that accommodates cognitive and sensory diversity, ensuring that features do not place undue demands on users, but rather enhance usability and accessibility for all.

- **Psychophysiological State:** A person's physiological and psychological state can significantly influence how they perceive and process stimuli. Factors such as fatigue, stress, or anxiety directly affect cognitive capacity and attentional resources, reducing the ability to engage with relevant stimuli or suppress distractions. Research has shown that acute stress impairs intention-based attentional allocation, enhancing stimulus-driven selection and leading to increased distractibility during tasks that require focused attention [346]. Additionally, mental fatigue has been found to reduce the ability to suppress irrelevant information, further diminishing attention control and increasing susceptibility to distractions [123]. Anxiety, in particular, creates an attentional bias, characterized by difficulty disengaging from perceived threats and a more general interference effect based on the level of threat present in the environment [390].

- **Emotional Response:** People's emotional responses to stimuli, based on their basic physical characteristics (e.g., acoustic features, color, shape), can vary widely due to individual preferences and associations. For instance, in the study presented in chapter 6, participants exposed to the same drone sound reported contrasting emotional reactions: some found it soothing and calming, while others found it irritating. These emotional responses are significant as they shape the arousal's valence (whether positive or negative) associated with stimuli perception. Stimuli that evoke stronger emotional responses, whether positive or negative, are perceived as more salient and thus have a greater impact on attention and behavioral tendencies, influencing whether individuals approach or avoid the stimuli. Moreover, as we will explore in the next processing level, the emotional response to a stimulus can be reshaped after further processing, depending on the information it conveys or higher-level associations that emerge during interpretation.

Contextual Factors As previously mentioned, attentional selection is crucial for filtering relevant stimuli while suppressing others, enabling us to conserve limited cognitive resources [195]. Contextual factors play a fundamental role in shaping this process, determining which stimuli are perceived as relevant in a given moment and influencing how attentional resources are allocated. These factors add layers of attentional focus and suppression, helping prioritize which stimuli capture attention and are further processed, while minimizing others to prevent them from surpassing the threshold for identification.

- **Situational relevance:** Depending on the ongoing activity—whether performing a task, engaging in a conversation, assessing a situation, or even engaging in introspective activities like reflecting on a problem or visualizing something—individuals apply attentional and suppression overlays that adjust the salience of stimuli based on their relevance to the specific activity. For example, when participants were instructed to find a specific glowing box in a room filled with boxes, as demonstrated in the study presented in Chapter 3, their visual attention was directed toward the zones where the boxes were located, while other elements of the environment became irrelevant. When asked where their attention was focused, most participants reported being absorbed in the task, paying little attention to the drone flying in the room with them—unless it became necessary to plan their navigation or avoid the drone when it came too close (see chapter 5, section 5.4.4). In this case, the instructions were clear, and the relevant stimuli to focus on were well-defined, suggesting strong attentional and suppression overlays. However, in some scenarios, what is deemed relevant to the ongoing activity may not always be as clearly defined, allowing more secondary stimuli to be processed. Moreover, certain situations, such as social interactions, may introduce a level of subjectivity in determining which stimuli are relevant, leaving room for individual variation in attention allocation. In addition, multiple ongoing activities may compete for attention allocation and be prioritized accordingly. As illustrated in the example above, participants' safety momentarily took precedence over the task at hand, shifting some or all of their attentional resources toward navigating the drone's proximity before returning to the task. This temporary shift made the drone's stimuli more salient, before refocusing their attention back on the boxes and ignoring the drone once it was no longer a concern. This illustrates how the characteristics of ongoing activities can affect individuals' perception of their surroundings and, consequently, their processing of the drone's sensory outputs.

- **Produced Framing:** Frames are structures that can enhance or diminish the relevance of various aspects of a situation [37]. While individuals develop their own framing through knowledge and previous experiences [117], which aligns with the "personal expectation" factor discussed earlier, produced framing can also be intentionally used to shape people's expectations. In the first study presented in Chapter chapter 3, we utilized a socially-oriented presentation of the drone to enhance and positively influence its social perception (see section 3.2.6). Although this did not achieve its intended outcome, it effectively focused participants' attention on the drone's social aspects as discussed further in chapter 3, section 3.2.6. However, when the expected social cues were absent, this mismatch—referred to as expectation dissonance—created a gap between the users' expectations and reality. This led to a shift in attention from the intended focus to the absence of expected features, resulting in a more negative perception of the drone. Expectation dissonance can diminish user engagement and trust over time, especially if the discrepancy is not addressed. Therefore, aligning produced framing with users' expectations is crucial to maintaining positive experiences and ongoing interaction. Overall, our research demonstrates that produced framing can significantly affect people's attentional filters, ultimately making certain aspects of the drone more salient. Our findings showed the potential for produced framing to alter users' attentional filters, highlighting how it might be employed to prepare interactions or foster acceptance.

- **Task Demands:** Cognitive resources are limited, and processing stimuli consumes a portion of these resources [195]. As task demands increase, individuals often experience a reduced capacity to process secondary stimuli, leading to stronger suppression overlays [222–224]. High perceptual load has been shown to eliminate distractor processing [223], as seen in our studies where participants under demanding tasks—such as navigating a complex environment or completing a multi-step procedure—were able to filter out the drone's sound and focus more intensely on the primary task. In contrast, participants engaged in less demanding tasks displayed greater mental wandering, as predicted by perceptual load theory [222–224]. This suggests that when cognitive demands are high, attention narrows to task-relevant information, often resulting in attentional tunneling. While this focus can enhance performance by isolating critical details [214], it can also cause individuals to overlook peripheral stimuli, altering their perception and potentially leaving them unaware of important cues or hazards, such as the presence of a drone. This highlights the need to consider task demands in drone design to avoid unintended distractions or oversight during critical activities.

- **Task Priority:** Task priority, unlike task demands, heightens arousal by making a task feel more critical, thereby focusing cognitive resources to maximize success or avoid failure [48]. This heightened focus can limit the resources available for processing secondary stimuli. For instance, while catching a ball may be a routine task, the stakes change dramatically in high-stakes situations, where task importance is elevated, sharpening focus and reducing attention to irrelevant stimuli. Research has demonstrated that task priority can induce attentional tunneling, causing individuals to focus excessively on tasks they perceive as critical [302]. In our studies, this concept was observed in a competitive environment, where a participant performing under high-priority conditions experienced attentional tunneling and failed to notice the drone carrying an explosive cube. Task priority can also arise from personal perception; in the first study in chapter 3, one participant, despite lacking external pressure, became intensely focused on the task in order to perform well, which significantly shaped their attentional experience (see section 3.2.5). This illustrates how task priority, whether externally induced (as in chapter 5, see subsection 3.3.5) or self-imposed (as observed in chapter 3), can shift attention and alter individuals' responses to secondary stimuli, such as drones.

- **Senses availability:** Attention can be divided between different sensory inputs, especially when switching between senses. However, when one sense is primarily focused on monitoring a specific task, it may limit the availability of that sense to detect other stimuli. This is particularly evident in the attentional bias towards currently attended stimuli [105]. In our studies, participants reported this phenomenon (see chapter 5, section 5.4.4), explaining that they used their vision to focus on the task, which limited their ability to visually track the drone's position. As a result, they relied on auditory cues to locate the drone, meaning important information conveyed through visual outputs went unnoticed or unprocessed.

Ultimately, the interplay between personal and contextual factors results in a unique filtering of the drone's sensory information, involving both suppression (dampening irrelevant stimuli) and amplification (emphasizing relevant stimuli) of neural activations. When these activations surpass a certain threshold, the perceived cues are processed further, ranging from basic information extraction (e.g., location, movement) to higher-level interpretations (e.g., ascribing mental states, perceiving relationships) and projections of future states.

7.2.2 Level 2 – Comprehension & Interpretation

Once sensory cues from external stimuli are registered, they undergo a second level of processing involving comprehension and interpretation. At this stage, individuals move beyond mere perception of the raw signals and begin to assign meaning to these cues based on their past experiences [376]. We then consider an additional personal association level where emotional associations can exist separately from logical interpretations. The depth of this processing can vary, ranging from basic, intuitive comprehension to more complex interpretation and emotional associations.

- **Comprehension** refers to the process of understanding or grasping the meaning of something, either intuitively or through established knowledge and experience. Essentially, it addresses the "What?" question. In the context of drones' sensory cues, comprehension involves recognizing and interpreting these cues at different levels of complexity. This includes understanding that the drone's sound signifies its proximity, that rotating propellers represent a potential hazard, or that a displayed visual represents a sad face.
  - **Basic Comprehension** involves straightforward, intuitive processing. With a drone as an external source of stimuli, it includes recognizing that a sound is coming from the drone, determining its location based on auditory cues, and noticing changes in the drone's movement in response to these cues. Similar to face recognition, this level of comprehension requires minimal cognitive effort. It is mostly automatic and does not necessitate specialized knowledge or prior experience.
  - **Knowledge-Based Comprehension** builds upon an individual's prior experience and knowledge, enabling them to infer meanings that are not immediately obvious from sensory cues alone. This type of comprehension relies heavily on mental models developed through prior exposure. When these models are absent or incomplete, sensory cues may go unrecognized as meaningful information, or worse, they might

be misunderstood. For example, while external entities (like drones) may communicate specific information through their movements—such as intentions [344], directional cues [88], acknowledgment behaviors [192, 259], and even emotional expressions [79, 177, 322]—individuals without prior exposure might fail to detect or misinterpret these cues. A drone's hovering or sudden movement might be perceived as random, even if it was designed to convey direction or intent. The complexity and variety of these cues can lead to confusion or miscommunication. This layer of comprehension highlights the significance of familiarity, learned associations, and the complexity of the perceived cues. From a situational awareness (SA) perspective [115], this step is particularly prone to the influence of SA "demons," which are factors that can undermine effective comprehension.

First, individuals with inaccurate or incomplete mental models may misinterpret or extract incorrect information from what is perceived. Without proper understanding of how an entity behaves (whether a drone, robot, or living beings), someone might infer the wrong meaning from signals such as flashing lights, movements, postures.

Second, this layer of processing is subject to what is known as "complexity creep." This refers to the notion that as the complexity of a cue increases—requiring more cognitive effort to interpret—the likelihood of misunderstanding or disregarding the information also increases. This becomes especially problematic when cognitive resources are strained (as explained by the WAFOS demon [341]). The more mental ressources required to process these cues, the higher the chance they'll be either inaccurately processed or dismissed entirely. This is particularly critical in high-stress or resource-demanding situations, where mental fatigue can lead to lapses in understanding.

Finally, individuals have limited working memory, meaning that when too much information is required to navigate around an external entity, errors are more likely. For instance, if someone must remember a complex path an entity (such as a drone or robot) will follow to plan their movements, their working memory may become overwhelmed. Above a certain threshold, they may forget the next step, leading to miscalculations or inappropriate responses.

When these cues carry critical information—such as the drone's trajectory, intention, or proximity—misinterpretation or neglect could have problematic consequences, particularly in dynamic environments where rapid and accurate comprehension is essential.

This processing step is crucial from a performance perspective, especially in terms of anticipating an external entity's future behavior. Whether the entity acts as an obstacle or an ally, its perceived movements can significantly influence an individual's ability to perform tasks and shape their navigation strategies. For instance, in chapter 5, participants navigating a space alongside an autonomous drone noted that its simple and predictable movements facilitated their navigation. Understanding the drone's movements allowed them to better anticipate its trajectory and approach with greater confidence, knowing it would not abruptly change direction.

- **Personal Interpretation** refers to the subjective meaning individuals assign to information, effectively answering the "Why?" question. This interpretation can vary widely based on personal characteristics and context. For example, while one person might recognize that the drone is displaying a sad face (answering "What?"), their interpretation of this cue can differ. One individual might perceive the sad face as indicating that the drone is "sad" due to user actions [172], while another might interpret it as a signal of low battery or a technical issue. Others might simply recognize the sad face without attributing any deeper meaning, leaving the "Why?" question unanswered. Understanding the mechanisms behind these diverse interpretations requires further research.

  Previous studies have shown that people can assign meaningful interpretations to digital facial expressions of drones [172]. However, our research (see chapter 3) found that, in actual interactions, these expressions were perceived as relatively context-neutral and abstract, lacking specific relevance to the interaction context. Although participants easily recognized the expressions, their ability to extract nuanced emotional content or context-specific messages appeared limited. For drones to exert social influence and be regarded as social entities, their cues need to convey socially meaningful information. While chapter 3 discusses the relevance of communicative proxemics, this sensory processing approach provides a fresh perspective on why current drone designs may induce limited social influence. Nonetheless, indirect social influence might arise from other social agents present in the interaction context. Hence personal interpretation significantly shapes how a drone is perceived, from a simple flying object to a potential social entity. While the interaction context has been identified as a probable factor shaping personal interpretation, further investigation is needed to fully understand individual differences in this process.

- **Personal Association** refers to the emotional and cognitive connections individuals make with an external entity that go beyond logical interpretations. This layer of processing adds an additional dimension to how the entity is perceived, influencing both emotional reactions and cognitive assessments.

  Personal associations are deeply rooted in an individual's past experiences, personal dispositions, and emotional states. They can significantly alter the emotional valence and intensity of arousal triggered by the entity. For instance, someone with a strong affinity for technology and positive prior experiences with drones might experience feelings of curiosity and excitement when interacting with the drone, as observed in chapter 3.

This positive emotional response can enhance their engagement with the drone and lead to more favorable interactions.

Conversely, individuals with negative past encounters or general apprehension towards technology may perceive the drone—or any other external entity—differently. For example, in chapter 4, a participant described the drone's sound as reminiscent of a threatening device, something that could "chop your head." During cognitive appraisal (evaluation of whether the situation poses a threat to their well-being, detailed in subsection 4.6.1), such associations can evoke increased threat-related arousal, leading to heightened stress and a more cautious or negative attitude towards the entity. These emotional responses can significantly impact how individuals navigate around the drone, shape their overall interaction experience, and affect their perception of the drone's intent and potential risks. As discussed in Level 3 of this sensory processing framework, which addresses the projection of the entity's future state, these associations can guide expectations about the entity's behavior and influence decision-making processes in real-time interactions.

7.2.3 Level 3 – Projection of Future States

Building on the principles of situational awareness [114] and integrating cognitive processes related to attention and cognition, the final level of an external entity's sensory output processing focuses on projecting its future states. At this stage, individuals utilize information gathered from the earlier levels—comprehension and interpretation—to predict the entity's future actions, including its movements and behavior.

Accurate projection allows individuals to anticipate not only the entity's movements but also corresponding changes in key spatial dynamics, such as arousal stimulation, perceived threat, performance, and social appropriateness. For instance, an individual may predict that a drone will soon move away from a particular area, prompting them to move toward that location, expecting it to be safer when they arrive. However, such predictions depend on the individual's ability to make precise assessments of the entity's behavior over time. In chapter 5, participants emphasized how accurate projections were critical to shaping their navigation strategies. The drone's simple and predictable movements enabled participants to anticipate its trajectory confidently, adjusting their movements accordingly. Knowing that the entity wouldn't abruptly change direction allowed individuals to approach it with greater ease and less uncertainty.

Mental Models Projection accuracy heavily relies on the individual's mental model of the external entity's functioning [341]. Erroneous or incomplete mental models can lead to incorrect projections, sometimes with significant consequences [115, 341]. For instance, if an individual knows the entity is moving in a certain direction but is unsure of its speed, or if they misinterpret its direction (related to level 2 comprehension), they may mistakenly assume they have enough time to pass in front of it or follow an incorrect path. This scenario was observed with one participant in chapter 5, where an inaccurate projection of the drone's movements led to a potentially risky situation. If the drone is faster or closer than anticipated, individuals might not react in time, increasing the risk of collisions.

Complexity and Regular Updates The complexity of accurately projecting the external entity's future state, particularly in dynamic or fast-paced environments, can be mentally demanding, as indicated by previous works [213], with increased speed leading to greater perceived mental load. Similarly, when the entity's behavior is ambiguous or inconsistent with user expectations, individuals must continually revise their evaluation, leading to heightened cognitive and attentional demands. Although the ability to project future states provides significant advantages in spatial navigation and safety, it can also become mentally exhausting. If the cognitive demands of projection become too high, individuals risk experiencing cognitive overload. In such cases, if not prioritized over other competing tasks, this overload can lead to misjudgments, increased errors, and accidents, as individuals struggle to maintain accurate projections of the entity's movements. This can motivate individuals to maintain distance from the entity, both for safety and arousal regulation reasons.

7.2.4 External Entity's Spatial Significance

The multilevel processing of cues from an external entity culminates in a general perception of the entity, which is then integrated with other environmental stimuli within broader cognitive processes. These processes enable ongoing situational assessments that drive human behavior.

- If the processing of cues from the external entity generates significant physiological or psychological arousal, the entity's presence becomes relevant from an arousal regulation perspective. In such cases, the entity may be perceived as something to mitigate in order to prevent overstimulation. When this arousal can be moderated by adjusting the distance maintained from the entity, spatial adjustments serve as a regulatory strategy [122, 282] (see subsection 6.6.1).

- If the processing of the drone's cues from levels 1 to 3 generates significant physiological or psychological arousal, the drone's presence becomes relevant from an arousal regulation perspective. In such cases, the drone may be perceived as an entity to mitigate in order to prevent overstimulation. When this arousal can be moderated by adjusting the distance maintained from the drone, spatial adjustments serve as a regulatory strategy [122, 282] (see subsection 6.6.1).

- When the external entity is perceived as a potential threat, cognitive appraisal processes evaluate the level of threat [48,133] (see subsection 4.6.1). Here too, if the perceived threat can be alleviated by increasing distance from the entity, spatial adjustments function as a defensive strategy.

- If individuals interpret the entity as a social presence, with its cues conveying social meaning, they may adopt socially appropriate behaviors. The space maintained between themselves and the entity can serve as a powerful signal in regulating social appropriateness [163], making spatial adjustments a key social strategy (see subsection 3.4.1).

- Lastly, if the external entity is involved in an individual's task performance—whether as an interacting agent, an obstacle, or an ally—spatial adjustments can be made to support task objectives. In this context, the position relative to the entity becomes crucial for goal-oriented behavior, as proximity or distance directly impacts performance (see subsection 5.6.1).

Each of these dimensions—arousal regulation, threat perception, social appropriateness, and goal-oriented behavior—interact dynamically. For instance, engaging in a conversation with the drone may involve both social appropriateness and goal-oriented considerations, while a perceived threat may simultaneously trigger heightened arousal that exceeds an individual's acceptable threshold.

Ultimately, if the processing of the drone's cues assigns significance to it along any of these dimensions, and if spatial adjustment can effectively modulate that significance, the drone becomes a relevant factor in proxemic behavior. This significance will directly shape spatial interactions, as detailed in the following section.

7.3 **Dynamic Proxemic Fields –** A Multilayered Spatiotemporal Perspective

In this section, we introduce an advanced conceptual framework for understanding human proxemics in relation to external entities, including autonomous drones. This framework integrates multiple layers of proxemic potential, encompassing key functions such as defense, arousal regulation, task performance, and social communication. By incorporating these layers, we provide a comprehensive, multilayered model that captures the complexity of human-entity interactions in dynamic environments. This perspective accounts for both observed behaviors and anticipated responses, offering a robust foundation for analyzing spatial dynamics across various contexts.

7.3.1 Information Processing Overview

The interaction between personal and contextual factors leads to a unique filtering of an external entity's sensory information, involving both suppression (reducing irrelevant stimuli) and amplification (highlighting relevant stimuli) of neural activations. When these activations exceed a certain threshold, the perceived cues undergo further processing—ranging from basic sensory extraction (e.g., location, movement) to higher-level interpretations (e.g., ascribing mental states, perceiving relationships) and projecting future states.

This processed information may be used immediately or stored in memory for future reference, forming an internal record of the entity. Over time, stored information may be updated (e.g., new position), expire (e.g., becoming irrelevant), or simply fade from memory. Importantly, the way extracted information is utilized in subsequent cognitive processes provides top-down feedback on its relevance, shaping how future stimuli are filtered—whether amplified or suppressed in future information-processing cycles.

Entity-related information is then integrated into broader cognitive processes that continuously and mostly unconsciously shape behavior. These processes include cognitive appraisal, situational awareness, arousal regulation, and defensive mechanisms. They contextualize the external entity within the individual's situational experience, assigning it significance along four key dimensions: social interaction, arousal, defense, and performance.

This significance can vary considerably across these dimensions, though not entirely independently—for instance, the perception of threat often induces heightened arousal. To illustrate cases of unidimensional significance, a drone might be perceived as a mere obstacle (performance-related), a favored companion (social-related), a calming presence (arousal-related), or a flying threat (defense-related). However, in practice, it is usually a combination of these perceptions. Each aspect for which proxemics serves as a behavioral mitigation strategy—whether it's related to safety (Defensive Function), comfort (Arousal Regulation), performance (Goal-Oriented Behaviors), or social interaction (Communicative Function)—and where the entity has been evaluated as having situational significance, generates its own spatiotemporal value mapping, from which emerges a field of proxemic potentials. This process is illustrated through a simplified schema for one proxemic dimension in a drone encounter scenario (subsection 7.3.1).

7.3.2 **Value Mappings –** Threat level, Arousal, Social Appropriateness, or Performance

Each point in space is assigned a subjective value corresponding to the dimension being considered (e.g., threat level, arousal, social appropriateness, or performance). These values are relative to the entity's position, except for performance, which may be evaluated independently. We denote these mappings as $V_{dimension}(x, y, t)$, where dimension refers to the specific field being represented (e.g., V_{threat}, V_{social}), x and y are spatial coordinates, and t is the time at which the value is evaluated.

- **Threat-Level:** These values reflect the perceived threat that the entity represents at any given point in space. It's essential to note that this is not an objective measure of the entity's potential to cause harm, but a subjective assessment based on perceived cues and personal factors, such as an individual's perceived ability to cope with the threat. As

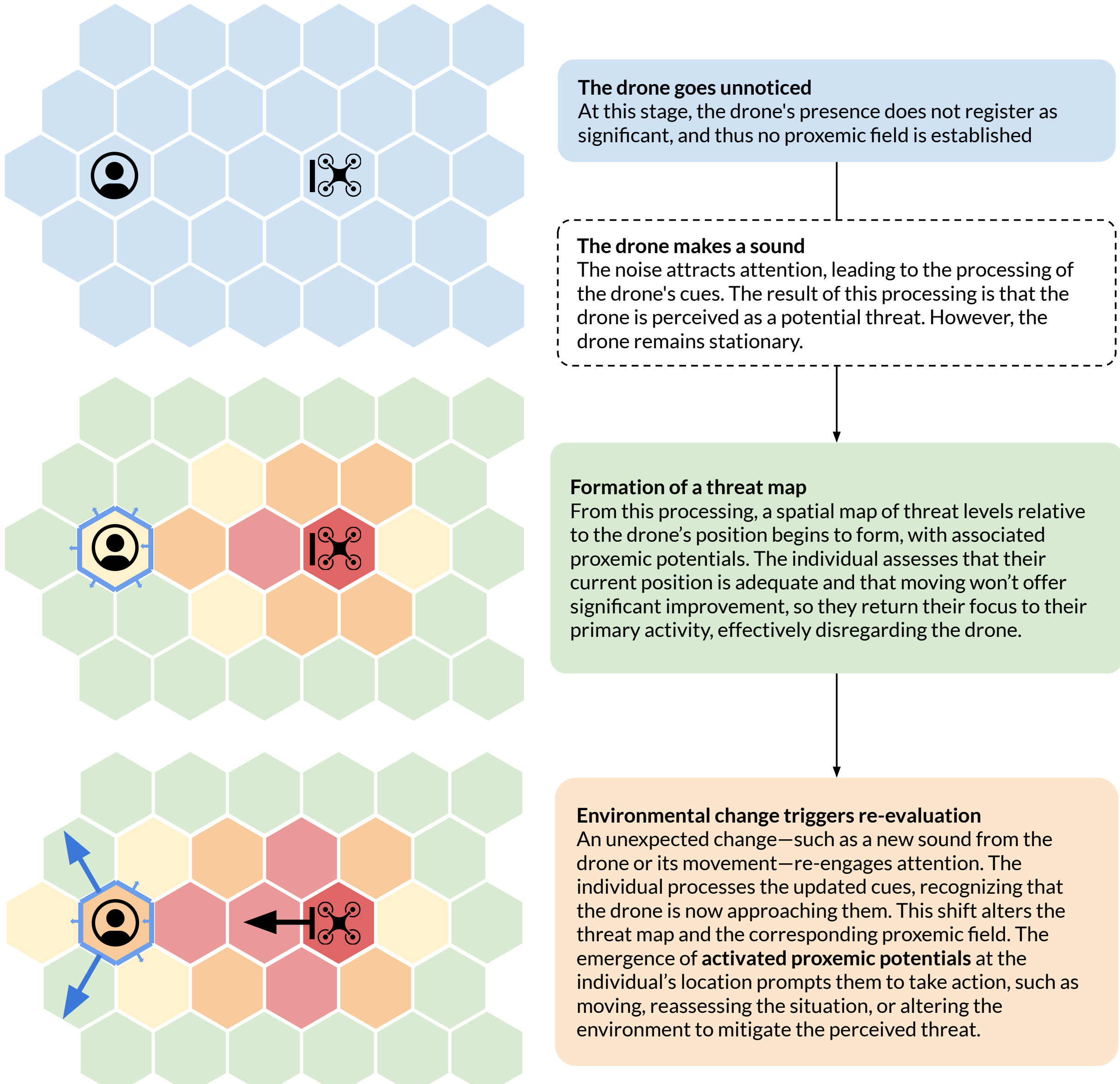


Figure 7.3: Illustration of the process through which proxemic drives emerge from the dynamic perception and interpretation of the external entity's sensory outputs in a drone encounter scenario. Initially unnoticed (no proxemic influence), the drone becomes perceived, prompting a spatial mapping of threat levels relative to its position. At this stage, no movement is required. However, as the drone begins moving toward the individual, a reassessment occurs, with increased perceived threat in the space. This heightened threat level triggers significant proxemic responses, motivating the individual to move toward safer areas.

detailed in chapter 4, which covers the defensive proxemic function in HDI, the perception of threat emerges from a combination of these external cues and internal processing. For instance, if a cue signaling danger—such as a hazardous object being carried by the drone—is not perceived, the threat level values will likely be minimized, as seen in chapter 5, where participants treated the drone as a simple obstacle and paid minimal attention to it. Threat values can take various forms and be incomplete; unknown values that are perceived as potentially high may trigger risk-assessment behaviors, characterized by cautious movements aimed at gathering more information for better evaluation. Ultimately, this mapping is highly subjective and depends on an individual's perception of the entity's cues. Given the common perception of drones as both physical and privacy-related threats, this mapping often plays a key role in shaping interactions in drone encounter scenarios.

- **Arousal Stimulation:** Arousal values represent the subjective level of mental or physical stimulation triggered by the entity's presence, perception and interpretation of its cues, encompassing both the intensity and valence of the experience.

  Intensity refers to how strongly the external entity affects an individual's arousal, ranging from low (minimal stimulation) to high (overstimulation). Arousal intensity often increases in response to perceived threats, as individuals mobilize resources to handle stress. For example, the drone's presence raised alertness in certain scenarios, increasing arousal levels (see chapter 4).

  Valence, by contrast, refers to whether this arousal is perceived positively or negatively. In some cases, arousal with a positive valence such as curiosity about the drone (see chapter 3) or the drone's soothing auditory presence prompted individuals to seek proximity to maintain optimal arousal (see chapter 6). Conversely, arousal can take on a negative valence when the drone is seen as disruptive or overwhelming, especially when its ouputs lead to sensory overload or excessive arousal, as observed in situations where individuals were already stressed by other tasks (see chapter 5 and chapter 6).

  Importantly, the balance between intensity and valence is crucial. While moderate levels of arousal with positive valence can enhance engagement or curiosity, exceeding a certain intensity threshold can shift the valence from positive to negative. This explains why individuals might adjust their spatial positioning relative to the entity—not necessarily to avoid all arousal, but to regulate it to an optimal level. Such adjustments aim to maintain stimulation that is beneficial without becoming overwhelming.

- **Performance** Performance values represent how well a given position supports the individual's ability to complete a task, and become relevant the external entity acts as either an obstacle or an aid. These values often depend on spatial factors, such as navigating between two locations, as highlighted in chapter 5 and chapter 3. However, they are not always linked to physical space. In chapter 6, participants engaged in mentally demanding tasks, where the drone's disruptive noise negatively affected performance, prompting them to use spatial adjustments to mitigate its impact. Additionally, performance values can change over time, especially when tasks are time-sensitive. For example, in chapter 5, participants adjusted their speed as time constraints intensified, indicating that the perceived performance value of their current location decreased as time passed.

- **Social Appropriatness** Social appropriateness values relate to how suitable a person's spatial behavior is within the context of social communication (e.g., relationship dynamics), social norms, and expectations. This dimension becomes relevant when the entity's cues are interpreted through a social lens, leading to social influence, or when the entity is perceived as a social actor. It also includes situations where individuals consider how their actions might be perceived by others in the environment. In chapter 3, we examined how these values emerge during HDI. Notably, if cues designed to evoke social interaction are not perceived as such, social influence will not occur, meaning no significant social appropriateness values will emerge.

Non-Linear Spatial Distribution The variation of these values across space is not necessarily linear—two nearby points may have similar, slightly different, or even drastically different values depending on the context. For instance, while arousal stimulation might be acceptable at a certain location, a minor movement might lead to a significant change in arousal levels. A point that is one step away might not differ much, but moving closer could dramatically increase arousal, shifting from a manageable to an overwhelming state.

Dynamic Temporal Changes The spatial value mapping can remain relatively stable over time, such as when the entity is stationary and the environment is unchanged. However, in dynamic situations—such as when the a drone is moving, or when individuals need to reach a specific location within a limited timeframe—the values assigned to each point in space change as time progresses. These changes can be anticipated when projecting the entity's future states, or result in a continuous monitoring if considered unpredictable. Moreover, these changes are not necessarily linear; the rate and magnitude of value changes can vary significantly over time. The temporal aspect must be considered when evaluating proxemic potentials, as it directly influences how individuals navigate space. For instance, behaviors such as "waiting," observed in our studies, can be understood as individuals delaying movement to optimize their path based on anticipated changes in the environment or threat levels. Additionally, unpredictability significantly impacts behavior, as individuals cannot plan their movements too far in advance. Instead, they must regularly update their value mappings through continuous information-processing loops. This need for real-time updates consumes greater cognitive resources, as individuals must constantly reassess their proxemic fields to make informed decisions under evolving circumstances.

7.3.3 Proxemic Potentials

Definition

Proxemic Potential (noted *PP*) represents the motivating "drive" that influences a person's movement based on the values $V_{dimension}(x,y,t)$ associated with different locations over space and time. Proxemic potential builds up from the differences in values between where a person currently is and where they could go in the future. This difference is evaluated through the temporal integration of values along possible paths—how long the values along the route are experienced—while also accounting for factors like travel time and path difficulty (e.g., required effort). However, proxemic potential alone doesn't guarantee movement; it must surpass a certain level, called a **threshold of activation**, before a person is compelled to act. A proxemic potential that surpasses this threshold is called Activated Proxemic Potential (APP).

To help visualize this concept, proxemic potential can be loosely compared to potential energy in physics, where objects move from areas of high to low potential energy, but only if certain barriers (like friction) are overcome. Similarly, proxemic potential must surpass the threshold of activation before movement occurs. While this analogy provides a helpful conceptual model, proxemic potential is inherently subjective, multi-dimensional, and context-sensitive, making the comparison a high-level simplification.

Importantly, we differentiate between the psychophysiological triggers that indicate a need for regulation of perceived threat, social appropriateness, arousal, or performance—which may arise solely from the value of the individual's current position (e.g., high threat levels or sensory overload)—and the actual drive to move, which we define as proxemic potential. Proxemic potential incorporates more than just the immediate position's value; it includes considerations of surrounding values, distance, time, and the relative difficulty of the path. This distinction helps account for behaviors that cannot be explained by considering the current position alone.

- **Considering the Path's Values:** By accounting for the values of all points along the potential paths, we can understand behavior that might seem counterintuitive if only comparing start and end points. People don't always take the most direct route; they often navigate more complex, curved paths. For instance, an individual may pass through a higher-threat zone to reach a safer location, which may seem confusing at first. However, considering the proxemic potential of the entire path explains this—passing through riskier zones can be justified when the total potential of the path leads to a better end point.

- **Time is of the Essence:** Proxemic potential is shaped not only by where a person is or wants to go but also by the timing—when they'll reach different points along the path and how values along the way change over time. This becomes critical in dynamic environments, such as when a moving drone alters the proxemic field or during time-constrained tasks. Individuals may decide to wait, speed up, or choose a different route, as seen in our study (chapter 5).

- **Path's Subjective Demand:** Within a given mapping of values, some locations may appear highly attractive. However, additional factors can negate or diminish the Proxemic Potential associated with these locations. One critical factor is the effort required to traverse a path relative to an individual's perceived ability. For example, if reaching a location with a desired value requires a movement speed that exceeds what is feasible for the individual, the Proxemic Potential for that path will be nullified or become negative. It is important to account for the path's subjective difficulty, as it varies based on an individual's physical capacities, which can be influenced by factors such as age or impairments. This consideration helps explain situations where, despite a need for regulation, spatial adjustments may no longer be viable due to the perceived difficulty of reaching the desired location within the required time.

- **Drive to Move Versus Need to Regulate:** It's important to distinguish between two related but distinct processes: the psychophysiological triggers that indicate a need for regulation, which may arise solely from the value of the individual's current position (e.g., high threat levels or sensory overload), and the drive to move, which is influenced by proxemic potential—factoring in additional elements like whether spatial adjustment is perceived as feasible or effective (value comparison weighted by distance, time, and difficulty).

  This distinction helps explain behaviors like subtle spatial adjustments even in the absence of immediate danger or overwhelming discomfort. Small movements may occur because they offer slight improvements without much effort. Even when the value differences across locations are minimal, these minor shifts can easily enhance positioning or comfort.

  Conversely, movement might not occur even in situations of high discomfort or threat. For instance, a person may perceive significant danger in their current position, creating a strong need for regulation. However, if moving to a safer location is difficult—whether due to time constraints, distance, or path complexity—the proxemic potential (drive to move) may be weakened. In such cases, proxemic potential may fall below the threshold needed to trigger movement, despite the ongoing need for regulation.

  When spatial adjustments aren't feasible or are restricted (such as when someone is confined to a specific area), individuals may resort to other regulatory mechanisms. These can include cognitive strategies (e.g., blocking out or ignoring discomfort) or actions to alter the environment itself. Defensive behaviors like freezing (cognitive response) or defensive attacks (acting on the environment) serve as alternative strategies when relocating is not an option.

Multiple Layers

While we now understand how proxemic potential emerges from the mapping of values within a single dimension, a key question remains: how do multiple relevant dimensions and their associated proxemic potentials interact to shape behavior? Throughout our work, although we have focused on one proxemic function at a time, we've consistently observed the influence of the others. This suggests that individuals' use of space around external entities—whether autonomous systems, other humans, or digital agents—is driven by multiple factors rather than a single motivation.

When multiple proxemic fields (e.g., threat, arousal, social appropriateness, performance) influence the same environment, individuals experience a combination of forces that guide their behavior. These fields are not always distinct; proxemic potentials from different layers can overlap, reinforcing one another and making paths that satisfy multiple needs more prominent. However, these fields can also conflict, pulling individuals toward different locations. In cases of conflict, the stronger driving force from one dimension may trigger a "remapping" of values in the less influential dimension. Through various strategies—cognitive, behavioral, or environmental—the values within the weaker field are altered, reducing their associated proxemic potential and rendering them insignificant, effectively resolving the conflict. Alternatively, this process may allow new, non-conflicting proxemic potentials to emerge, better satisfying the needs of both dimensions as in the illustrative Figure 7.4.

Activated Proxemic Potentials In line with our conceptualization, we propose that only proxemic potentials that exceed the activation threshold for their dimension become driving forces and contribute to the balance of proxemic behaviors. This means that even if there are mapped dimensions like social appropriateness, threat level, or arousal, if no activated proxemic potential is present along the considered path (i.e., no sufficient drive to trigger movement), these factors will not influence people's proxemic decisions. Importantly, because we consider paths across space and time rather than fixed positions, activated proxemic potentials from these dimensions may emerge later in the journey or at a different time (e.g., if the value mapping is time-dependent).

Value Barrier We anticipate the presence of "value barriers" or "critical zones," where even in fields with generally low proxemic potential, small positional changes can cause significant shifts in potential. Crossing these value barriers can trigger immediate, strong, but brief repulsive effects, pushing individuals away from specific areas. These sudden changes can be understood as steep gradients in the value mapping. Just as a single step can move someone from a busy road to a safe sidewalk, from stable ground to the edge of a precipice, or in our case, from avoiding a drone to colliding with it. This phenomenon is illustrated in Figure 7.4.

Locked Driving Potential Once a proxemic potential in a given dimension exceeds its activation threshold, it becomes "locked in" and cannot be deactivated by competing influences from other dimensions; only changes of values $V_{dimension}$ within the same dimension can affect its state. In other words, once the motivation to move in response to a specific need is activated, it remains active regardless of competing drives from other dimensions. This is why activated proxemic potentials that oppose each other across different dimensions are considered to be in conflict rather than simply compensating for one another. For example, as illustrated in Figure 7.4, the drive to reach a specific objective is not nullified by the repulsive effects of threat assessments. In such cases, where no alternative path is deemed satisfactory while avoiding the repulsion zone, a remapping of values from one or both dimensions may be required.

Competing Potentials When multiple activated proxemic potentials (APPs) from different dimensions are present, determining the exhibited behavior involves a process of combining and comparing these competing potentials. When APPs from different dimensions overlap and are positive, they reinforce each other, making paths that satisfy multiple needs more prominent. However, if an APP encounters a conflicting one, the overall drive to follow its path is diminished. Aggregated APPs still compete with single ones, and the ultimate choice may not always favor reinforced APP or nullify the reduced ones. In Figure 7.4, path "C" was ultimately selected despite having a lower performance score compared to path "B", because path B was in conflict with the threat-related APP "A".

Conflicting Cases When significant proxemic potentials (APPs) from different dimensions direct individuals toward conflicting locations, a conflict arises. In such situations, the dimension with the lower APPs, which is less urgent, may undergo a process of re-mapping. Individuals use various strategies to alter the values of this dimension, including spatial adjustments such as waiting or changing speed to align with a more favorable mapping (as illustrated in Figure 7.4). For instance, an individual might move quickly to reach a distant location with better performance values, even if it deviates from the shortest path, or wait for a threat (e.g., a drone) to move away, allowing for a safer, more direct route to the objective, as observed in chapter 5. Additionally, individuals may act on sensory processing to influence their proxemic evaluation. This can involve altering the physical reception of external cues, such as wearing headphones to block the sound of a nearby drone or deliberately avoiding visual contact to block potentially threatening stimuli. Alternatively, individuals may engage in cognitive filtering, selectively ignoring received stimuli. This was observed in chapter 6, where individuals remained at a fixed position near a drone while filtering out its sound, suppressing arousal and threat responses even though the stimuli were physically present.

7.4 Chapter Conclusion

In this chapter, we introduced a holistic conceptualization of human proxemic behaviors around external entities, including but not limited to autonomous systems like social drones. By tracing the process from the physical cues emitted by an entity to the proxemic behaviors exhibited by individuals, we provide a comprehensive answer to **RQ1**: What motivates individuals' proxemic behaviors around drones, and how do they manifest? Our goal was to address the complex set

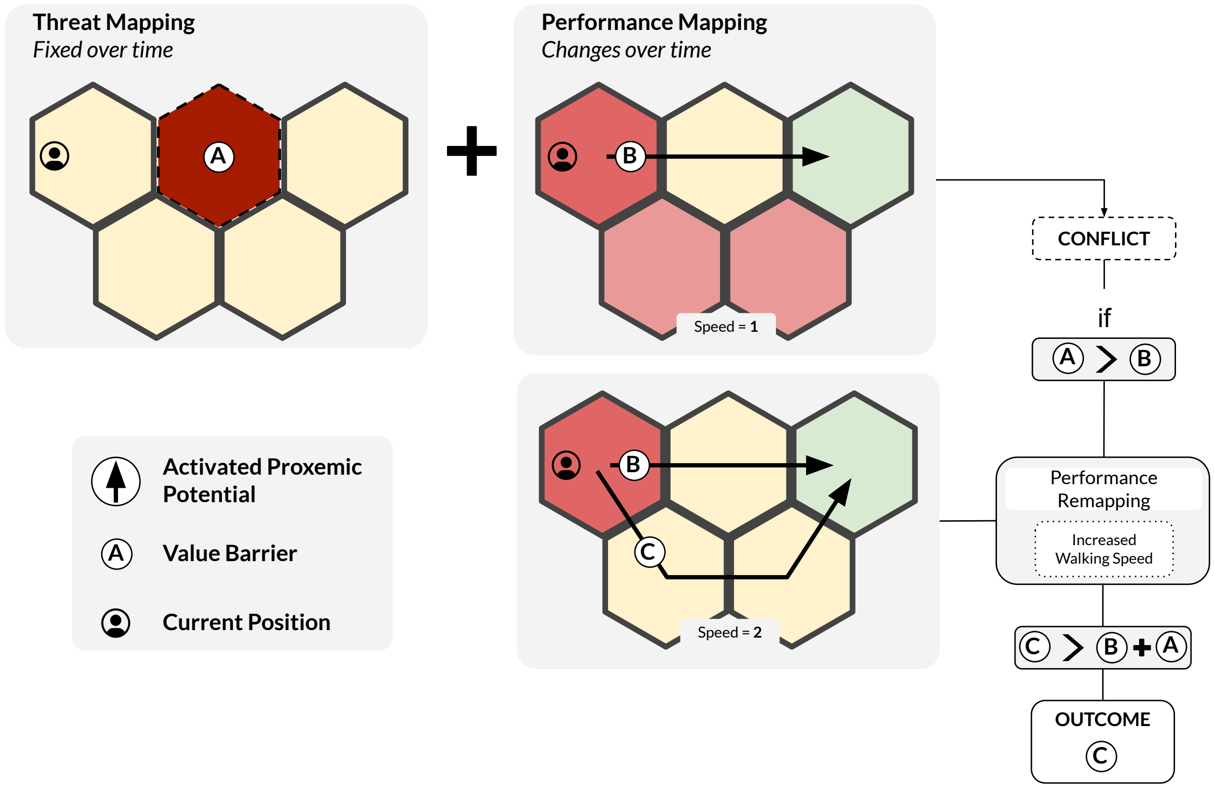


Figure 7.4: Illustration of the interaction between two proxemic fields, using 5-cell models for both threat and performance mappings. The figure demonstrates how a conflict can arise between significant driving forces (Activated Proxemic Potentials) from different proxemic motivations, and how this conflict can be resolved by altering the values of one dimension through alternative strategies. This adjustment either removes the conflicting weaker proxemic potential or allows the emergence of new, significantly attractive paths that satisfy the needs of both dimensions, as shown with the appearance of path *C* when the individual's speed is increased. In the figure, "*A*" is a value barrier, which represents a steep gradient in the value mapping resulting in an immediate repulsive force that pushes individuals away. A key example of such a barrier is the drone itself, which would function as a form of collision avoidance

of factors shaping this process, moving beyond existing frameworks that often rely on outdated knowledge. We demonstrated how today's deeper understanding of mechanisms like information processing can inform and update these frameworks.

Our model addresses key limitations in current approaches to proxemics within human–robot and human–drone interactions by considering the multiple, dynamic motivations driving individuals' spatial adjustments. While Leichtmann et al. [227] suggested tailoring proxemic frameworks to specific studies, our model provides a more unified approach—integrating multiple proxemic functions and capturing their interactions within a single dynamic framework.

A key innovation of our conceptualization is the introduction of a multidimensional, context-dependent mapping of spatial significance. Rather than treating proxemic behavior as a static response to a single factor (e.g., perceived threat or task relevance), our model recognizes that approach and avoidance forces emerge from the interaction of diverse motivational dimensions—such as social appropriateness, performance, arousal regulation, and perceived threat. These forces function akin to potential energy, triggering movement or remapping when they exceed a certain threshold.

This approach not only aligns with and extends foundational proxemics theories (see section 2.2.1) but also offers a novel framework for studying proxemic behavior in dynamic environments. By encompassing all relevant proxemic functions explored throughout this work, our model provides a scalable and adaptable perspective—one that can inform research across human–robot interaction, human–drone interaction.

7.4.1 Final Remarks

Model's Application

While our framework encompasses a broad range of mechanisms—potentially appearing complex at first—its application remains straightforward. In research settings, it provides a structured approach to anticipating and analyzing proxemic behaviors by mapping sensory processing to situational assessment across the four key proxemic dimensions: threat, social appropriateness, performance, and arousal. Researchers can use this framework to design experiments that manipulate specific proxemic factors, analyze their behavioral impacts, and refine methodologies such as interview protocols or observational coding schemes to better capture individual differences in proxemic responses.

Beyond research, our framework offers practical insights for mitigating and shaping the spatial influence of external entities in real-world settings. For example, it highlights key intervention points—such as sensory cue design—to help create less intrusive and more intuitive interactions with autonomous drones.

From an industry perspective, this model serves as a valuable tool for designers and engineers working on autonomous systems, robotics, and smart environments. By understanding how design choices influence proxemic behavior—whether through altering salience, integrating communication cues, or refining movement patterns—developers can create more user-friendly, context-aware, and socially intelligent systems. This approach not only prevents unintended negative effects (e.g., overstimulation, misinterpretation) but also actively enhances engagement, efficiency, and safety in human-machine interactions.

Although drones serve as the primary case study in this work, the framework extends beyond aerial robotics. It is equally applicable to autonomous ground robots, interactive AI systems, and virtual agents, making it a versatile tool for research and development in human-machine interaction.

Proxemic Pillars

This conceptualization is shaped by both our empirical observations across chapters and existing cognitive and proxemic theories. As introduced in the literature review (see section 2.2.1), key concepts from proxemic research have been central to our approach and have been further consolidated through our findings as detailed below.

1. **Perceiving and interpreting sensory inputs forms the initial stage of proxemic process.** Early proxemic models identified this as a crucial element, but our understanding of how sensory inputs are processed has evolved significantly. We have explored this foundational pillar in depth to gain a clearer insight into how sensory processing influences subsequent mechanisms that drive proxemic behaviors. This exploration is informed by contemporary advances in information processing theory, which offer a more nuanced understanding of how sensory inputs shape behavioral responses.

2. **Proxemic behaviors are mostly unconscious.** The mechanisms involved in information processing and situational assessment that determine proxemic behaviors are largely automatic and unconscious. Although this unconscious aspect is not a distinct feature of the model itself, it has been crucial to our study of proxemic behaviors. This unconscious processing allows for more natural variations in spatial responses, influenced by personal and contextual factors. Controlled settings, such as the stop-approach procedure used for safety and replicability in chapter 4, constrain participants to process situations in more deliberate and uniform ways, which contrasts with the more intuitive and spontaneous nature of proxemic responses observed in less controlled environments.

3. **Space serves multiple functions.** Our research reveals that spatial adjustments relative to external autonomous systems like drones serve diverse functions—each interconnected and potentially relevant depending on context. Rather than identifying a single dominant function, our findings demonstrate the necessity of integrating all possible motivations (e.g., social, defensive, performance, arousal regulation) within a comprehensive model of human–drone proxemics.

4. **Individual characteristics and contextual factors can significantly influence the proxemic process and its outcomes.** This pillar has been reaffirmed throughout our studies, with post-experiment interviews and individual measures proving essential to understanding the wide variety of behaviors observed. Our integration of sensory processing within the overall proxemic process offers new insights into the origins of these individual differences, though further research is needed to fully explore how factors at specific levels (e.g., interpretation or association) drive these variations.

A Framework to Understand the Use of VR

In subsection 4.6.1, we introduced a methodological protocol designed to enhance the ecological validity of virtual human–drone proxemic studies and facilitate their external evaluation. The first step involves identifying the key cognitive and behavioral mechanisms associated with the variables under study.

This initial step can often be complex, especially when proxemic behaviors are not the primary focus of the study. Researchers may lack in-depth knowledge of the cognitive processes that shape proxemic responses, making it difficult to interpret findings accurately without extensive prior reading. Our model simplifies this process by enabling experimenters to situate the variables under investigation within the broader proxemic process. By doing so, they can easily identify the mechanisms that precede and follow those variables, offering a more structured understanding of how proxemic behaviors unfold.

The second step of the protocol focuses on evaluating how virtual reality might impact the processes identified in the first step. Our model streamlines this evaluation by providing a clear framework for identifying where and how discrepancies may emerge between the virtual environment and real-world interactions. This includes assessing how sensory inputs are processed, how situational awareness is formed, and whether any cognitive or behavioral adjustments may differ in a VR setting compared to real-world contexts.

Finally, since our model integrates and extends the previously examined proxemic functions, the insights gathered throughout the previous chapters remain applicable. The approach we employed when designing experimental virtual environments—guided by the literature in subsection 2.3.2 and the insights collected throughout our work—is further reinforced by the new emphasis on sensory experience added in our conceptualization of proxemic behaviors. Our approach for designing VR experimental environments focuses on accurately replicating real-world sensory dynamics, crucial for Level 1 perception, where sensory inputs are detected and registered. This includes simulating the drone's spatial location, potentially threatening elements like moving propellers, and addressing VR challenges like distance compression. At Level 2, where comprehension occurs, a strong sense of presence is key. High presence allows participants to interpret virtual cues as real and potentially harmful, whereas low presence reduces the realism of these interpretations. Finally, in the situational assessment phase (Level 3), participants rely on these sensory and interpretive processes to decide how to act. Ensuring realistic sensory cues and interpretations, as well as similar action possibilities, supports valid situational assessments, aligning VR behaviors with real-world outcomes.

Chapter 8

Summary and Reflections on Thesis Research

8.1 Introduction

As autonomous drones become more integrated into everyday environments, understanding the proxemic behaviors between humans and drones is crucial for ensuring their efficient and harmonious integration. This thesis has addressed key challenges in this domain, presenting *Empirical*, *Methodological* and *Theoretical* contributions [380] to the field of Proxemics, Social Drones and Human–Drone Interactions, that advance our understanding of human-–drone proxemics, broader interaction design, and the use of virtual reality (VR) as a research tool. These contributions are outlined in this chapter and summarized below.

#1 Exploring Proxemic Functions in Human-–Drone Interaction As suggested by the literature, we examined the relevance of four key proxemic functions—Communicative, Protective, Goal-Oriented, and Arousal Regulation—by answering a common question: What is their role in Human–Drone Interaction? Each of these functions is explored in dedicated chapters (Chapters 3 to 6), which involve a condensed theoretical background, empirical assessments of their relevance, practical reflections on their application in HDI, and concrete guidelines for researchers to adopt these frameworks. Comprehensive answers to each sub-research question are provided in the conclusion section of the respective chapters.

By introducing these tools, we significantly advance the theoretical groundwork for interpreting human–drone proxemics, equipping researchers with novel frameworks that go beyond prior empirical studies. Additionally, we highlight critical design considerations that arise from applying these proxemic lenses to HDI. While these contributions represent substantial advancements, they also revealed limitations in the existing frameworks, which led to the development of our comprehensive model of human proxemics when interacting with external entities, detailed in chapter 7, and representing the thesis's central contribution.

#2 Developing a Comprehensive Model of Human-–Drone Proxemics A central contribution of this thesis (answering **RQ 1** and RQ 1.5) is the development of a comprehensive, integrative model of human proxemic behavior when interacting with autonomous and interactive entities, presented in chapter 7. While derived from studies on drone interactions, the model is not specific to drones. Instead, it provides a generalized framework for understanding, predicting, and interpreting human proxemic behaviors across various external agents, including ground robots, but also potentially intelligent furniture, and even "non-living" objects that exhibit movement or responsiveness.

Rather than merely categorizing proxemic functions, this model dynamically integrates them, revealing their interactions, dependencies, and cognitive underpinnings. By incorporating sensory integration, cognitive appraisal, and adaptive spatial regulation, it advances beyond existing frameworks, offering new insights into how individuals process and respond to autonomous agents in real time.

While informed by human–drone interactions, the model's core principles extend to broader human–robot and human–autonomous system interactions, making it a valuable tool for research in interactive technologies. This generalized perspective is developed throughout Chapter 7, with key insights synthesized in the Conclusion.

#3 Contributions to Broader Human-–Drone Interaction Beyond our proxemic focus, we addressed several key gaps in the broader human–drone interaction literature. By investigating variables such as framing, flying height, public perception of social drones, drone sounds, and the interpretation of social cues, we contributed to a more comprehensive understanding of HDI. These findings, which help fill gaps in the field, inform the design of autonomous drones and motivates future research, are summarized in section 8.4.

#4 Virtual Reality in Human–Drone Proxemic Research In addressing **RQ2**, we developed a comprehensive methodological protocol for employing VR in human–drone proxemics studies. Grounded in both extensive literature review and empirical research, the protocol seeks to enhance the ecological validity of VR environments while ensuring transparency in methodological decisions. This framework allows future researchers to assess and refine the validity of VR studies in this domain. Additionally, we contributed practical guidelines for those new to VR technology and made available reusable resources, including code, virtual environments, and other implementation tools.

Together, these contributions represent significant advancements in understanding human–drone proxemics and designing autonomous drones. They provide both practical tools and theoretical models that will help guide future research (with some suggested research directions in chapter 9), ensuring that drones can be integrated into human environments in a safe, efficient, and harmonious manner.

8.2 Exploring Proxemic Functions in Human--Drone Interaction

8.2.1 Social Proxemic Influence in HDI

The role of social proxemics is explored in detail in subsection 3.4.1. Drones can influence social proxemics by adhering to social norms, reflecting intimacy levels, or responding to social cues, leading individuals to unconsciously maintain appropriate social distances from them [24, 163]. Our findings indicate that while this mechanism has relevance—especially in line with the equilibrium model of intimacy [24]—its overall influence is limited due to the mechanical design of drones and the lack of a meaningful social dimension in most contexts. For many participants, drones are not perceived as social entities, and there is often no clear need for them to be, which reduces their social impact.

From a design perspective, we questioned whether drones should be perceived as social entities or simply as objects, as detailed in subsection 3.4.1. Building a social connection with users can be beneficial [54], but it isn't always necessary. Viewing a drone as a social entity may trigger proxemic behaviors that increase distance and limit close interaction, as social entities require appropriate social distancing unlike inanimate objects.

So, when should drones be social? The true benefit of perceiving drones as social lies not in the creation of socially appropriate distances, but in their ability to shape people's perceptions and responses to other proxemic mechanisms (e.g., defensive, arousal regulation). Prior research supports this: adding anthropomorphic features to a harmless virtual drone increased distancing [383], suggesting that the modification only triggered the need for socially appropriate distance without improving overall perception. In contrast, adding a face to a real drone reduced distancing by covering threatening elements like propellers [389]. Designers should consider the context-dependent benefits of making drones social. For instance, in high-stress situations like search and rescue, a social connection with the drone could help victims feel less isolated and divert their attention from distressing elements, easing their anxiety. Conversely, adding social features, such as a smiley face, to a robotic arm in a factory might create unnecessary distractions where performance is prioritized and social interaction is irrelevant.

8.2.2 Defensive Spatial Behavior in HDI

The role of the defensive proxemic function in HDI is explored in detail in subsection 4.6.1. If autonomous drones are perceived as a potential physical, social or privacy-related threat, it may trigger a set of defensive behaviours, from risk assessment to attacks [44], aiming to preserve oneself integrity. Among these behaviours, maintaining a safety margin allows individuals to manage the perceived threat and escape if necessary, illustrating the defensive function of proxemic behaviors.

Our work, presented in chapter 4 and chapter 5 supports the role of the defensive proxemic function in HDI, with our measures aligning well with expectations derived from cognitive appraisal theory and the situational awareness model (see subsection 4.6.1). This provides a theoretical foundation for understanding human behavior around drones from a threat-management perspective. It highlights how autonomous drones operating in inhabited spaces can compromise individuals' well-being, underscoring the importance of maintaining safe distance from people. Close proximity can elevate stress and trigger defensive responses, posing risks to both people and drones. While autonomous drones may be safer and more socially integrated in the future, defensive proxemics is a key factor in current interactions, where drones are often seen as non-social and potentially threatening. However, this isn't inevitable—there are various design and behavioral strategies to mitigate such perceptions.

From a design perspective, there are instances where designers might intentionally want drones to be perceived as dangerous, such as in police operations or when transporting hazardous materials, to promote distancing. However, defensive distancing only works when people are aware of the threat. Our findings in chapter 5 highlight that inattentive individuals may underestimate a drone's danger and act unsafely. In these cases, drones need to actively attract attention to the risk they pose. Conversely, if closer interaction is the goal, our research outlines design and behavioral methods to reduce perceived threats (see subsection 4.4.3). Ideally, autonomous drones should be able to adjust their level of perceived threat dynamically, adapting their behavior and appearance (e.g., sound, visual cues) to suit different scenarios.

8.2.3 Goal-Driven Spatial Dynamics in HDI

Our research, detailed in chapter 5, introduces a new perspective on proxemic behavior by exploring a dynamic often overlooked in previous HDI studies: how individuals position themselves in shared spaces to optimize goal-related actions when interacting with or around drones.

As autonomous drones increasingly operate in environments where people conduct daily tasks—often involving independent navigation with occasional direct interaction—it becomes crucial to understand the goal-oriented aspect of proxemic behavior. Individuals' spatial decisions are shaped not only by social or defensive factors but also by the need to complete tasks efficiently. In collocated human–drone scenarios, our findings show that participants adjusted their positioning and movement to optimize task performance, with behaviors shifting based on the task's priority. While some participants demonstrated caution and maintained safety around drones, others exhibited a trade-off between efficiency and safety. In some cases, individuals sacrificed performance to remain at a safe distance from drones, whereas others prioritized task efficiency, ignoring potential risks posed by the drone. These behaviors highlight the importance of considering the influence of task priority on proxemics in HDI. We outline practical frameworks in subsection 5.6.1 to predict and address the impact of goal-oriented behaviors in HDI scenarios.

From a design perspective, it's vital for designers to recognize how task demands influence people's spatial awareness and behaviors around drones, as well as how drones can impact task efficiency. In environments where productivity is critical, such as warehouses, factories, or offices, drones must be designed to minimize their interference with human tasks. This includes avoiding becoming obstacles or distractions, which could trigger non-task-related behaviors such as threat management or social appropriateness. In shared workspaces, drones should avoid obstructing human movement and minimize any cognitive load they impose on users. We offer additional design recommendations tailored to work environments in section 5.4.4.

In summary, goal-oriented behaviors are pivotal in shaping proxemics in HDI. On one hand, individuals' focus on tasks influences their spatial decisions around drones. On the other hand, drones have the potential to either support or hinder human efficiency in task performance. For this reason, designing drones with an awareness of both goal-oriented behavior and proxemics is essential.

8.2.4 Spatial Regulation of Arousal in HDI

Arousal regulation refers to the management of one's physiological and psychological state in response to environmental stimuli [48]. In the context of proxemics, individuals strategically adjust their spatial behavior to modulate arousal: heightened arousal from stress or discomfort typically leads to increased distance from the source [122], while positively valenced arousal, such as excitement or interest, encourages approach behaviors [282]. Given that drones can elicit significant arousal through sensory stimulation, perceived threats, or fascination, understanding arousal regulation is crucial in shaping human–drone interactions (HDI). This aspect of human–drone proxemics has been explored in chapter 6.

In our initial work [57, 58] (see chapter 3), participants approached a virtual drone closely, driven by curiosity and excitement (see section 3.2.5). In later studies involving goal-oriented tasks (see chapter 5), participants viewed the drone as a potential threat, prompting them to increase their distance or speed to mitigate negative arousal (see subsection 5.5.2). Focusing specifically on drone sound in chapter 6, we found that increased sound intensity heightened arousal, correlating with annoyance and greater distancing. Participants maintained larger distances during cognitively demanding tasks to reduce distraction and stress, while some employed non-spatial strategies like filtering out drone noise.

Our research provides compelling evidence that arousal regulation significantly influences proxemic behavior in HDI. In subsection 6.6.1, we present to aid researchers in exploring the arousal regulation facet of human–drone proxemics in their studies.

From a design perspective, it is essential to consider how a drone's sensory outputs (sound, movement, appearance) can generate both positive and negative arousal as it can shape people's proxemics and overall user experience. Drones should adapt dynamically to situational factors and user states. In high-cognitive-load tasks, drones must minimize distractions and maintain safe distances to help users focus. In contrast, in low-stakes contexts, drones could foster positive arousal through engaging sound, movements or interactive designs.

8.3 A Comprehensive Model of Human Proxemics with External Entities

In Chapters 3 to 6, we examined human–drone proxemics through specific lenses, providing valuable insights into different proxemic functions. However, analyzing these functions in isolation overlooks their complex interplay. Human proxemic behavior is dynamic, context-dependent, and shaped by both sensory perceptions and cognitive appraisals. A function-specific approach—focusing only on social, defensive, or arousal-related proxemics—fails to capture the full range of spatial behaviors people exhibit in response to external entities (see section 2.2.1).

In chapter 7, we introduce a holistic model of human proxemics with external entities, tracing the process from the physical cues emitted by an entity to the proxemic behaviors individuals exhibit. While this model was developed using insights from human–drone interactions, it is not specific to drones. Instead, it provides a generalized framework for understanding, predicting, and explaining human spatial behavior in response to a range of external agents, including humanoid robots, pets, autonomous vehicles, and smart objects.

Our model addresses key limitations of existing proxemic frameworks applied to human–agent interactions. Current models often assume rigid, function-specific motivations, whereas real-world proxemic behavior emerges from the simultaneous interaction of multiple factors. While Leichtmann et al. (2020) recommended tailoring proxemic frameworks to fit specific contexts [227], our model integrates these varied frameworks into a unified approach.

It is based on a dynamic, context-dependent mapping of multidimensional values—including threat perception, social appropriateness, task performance, and arousal regulation. These values shape the spatial significance of an entity's presence, generating approach or avoidance forces that influence movement. This dynamic structure allows the model to be customized for different types of entities, depending on their sensory properties, interaction capabilities, and social significance in a given context.

8.4 Contributions to Broader Human–Drone Interaction

The title of this thesis, "Beyond Boundaries," aptly reflects the breadth of our contributions, extending beyond the confines of our proxemic investigations. Our efforts to address proxemic questions have resulted in significant contributions to the broader field of Human–Drone Interaction (HDI), often outlined in the discussion sections of each chapters, enhancing our understanding of critical design aspects for social drones [38]. These extended contributions are summarised below.

- **Framing:** In chapter 3, our first study (see section 3.2) delved into the concept of **framing** [117] applied to human–drone interactions [57]. We found that positive social framing successfully improved participants' initial perceptions of the drone, making the social dimension more prominent during interactions and shaping expectations. However, if these expectations do not align with what participants experience or clash with their existing beliefs, it may lead to dissonance upon interacting with the drone, resulting in ineffective or even negative reactions. These findings have practical implications for companies and public services deploying drones in public spaces, as they inform the presentation and design of drones to promote positive user perceptions and minimize potential negative reactions. Importantly, designers should consider the expectations they create and ensure they align with what users actually experiences.

- **Flying Height:** Additionally, we assessed the impact of different flying heights on people's proxemics. Our results revealed a misinterpretation in the field regarding the nature of the space below a flying drone. Notably, the term "tall" drone used in previous studies [107] may not be appropriate as drones do not physically occupy the space beneath them in the same way that ground robots and humans do. Participants apparently expect drones to ascend from lower positions, and consider the space beneath them as partially available. Our findings suggest that stationary drones should ideally fly above people rather than navigating around or below them in populated areas. This insight indicates that the zones below the drones remain accessible, providing ways to optimize the usable space in collocated contexts. However for direct interactions, engaging with the drone at eye level feels more natural when concerns about physical harm are absent [76, 109].

- **Envisioning the Future of Social Drones:** In the same study, we gathered participants' thoughts on future social drones, revealing their expectations regarding applications, interaction modes, and design concerns. Participants envisioned a future where people naturally communicate with their drones for various tasks at home and outdoors. They expressed a desire for personalized drones with advanced social features to coexist alongside more mechanical-looking models. Private drones would vary in appearance based on their affiliation and function, with legal restrictions and capabilities aligned to their intended purposes, including operation in emergency situations. However, the study also identified challenges for integrating drones into society, including high performance expectations, safety and privacy concerns, and complex design requirements.

- **Drone's Social Cues Interpretation:** In chapter 3 (see section 3.3), we investigated how participants interpreted a drone's digital facial expressions and gaze behaviors. Our findings indicate that while participants recognized these expressions, they perceived them as relatively abstract and context-neutral, lacking the ability to convey nuanced emotional content. This contrasts with previous research [172] and underscores the importance of context in interpreting social cues. The context influences how individuals respond to these cues, highlighting the need for future research to examine how contextual factors shape their significance and interpretation. Although our work suggests that social cues can enhance drone integration into various environments, understanding the subtleties of these cues is essential for conveying meaningful messages tailored to specific individuals and situations.

- **Drone's Threat Perception:** In chapter 4, we conducted semi-directed interviews to identify factors influencing perceived danger from drones and to explore participants' defensive behaviors. Through discussions supported by frameworks like Information Processing and Cognitive Appraisal, along with relevant research, we developed high-level guidelines for designers aimed at reducing threat perception and enhancing user acceptance of drone proximity (see subsection 4.4.3). These recommendations include: 1) Foster positive associations, 2) Communicate the drone's intentions, 3) Reduce the saliency of threats, 4) Enhance drone safety, and 5) Limit sensory inputs. While these guidelines focus on minimizing threat perception, it is crucial to acknowledge scenarios where threat evaluation is necessary, such as when drones transport hazardous materials, as explored in a subsequent study.

- **Effect of the Task at Hand:** In chapter 5, we explored how task priority influenced people's proxemics when navigating around a drone carrying either normal or explosive packages. Our study revealed that participants' mental workload and attention levels significantly impacted their perception of the drone, with some failing to notice the dangerous package due to task-related focus (potential tunnel vision effect, see subsection 5.5.3). A key takeaway for designers is that when workers' attention must be directed towards the drone, such as when they need updates on its status (e.g., carrying a hazardous object, obstructing their path), and it appears that surrounding users are not attentive due to tunneling or contextual impairment (e.g., the drone is out of sight), the drone should take proactive measures to attract users' attention. For instance, it could emit a beeping noise, as suggested by participants.

- **Drone's Sound:** Beyond exploring the proxemic impact of drone sound through the lens of arousal regulation in chapter 6, we contributed to the broader literature on drone sound perception. Our study examined how contextual factors (e.g., task nature) and individual traits (e.g., noise sensitivity) influence perceptions of drone noise (see section 6.5), as well as its effects on both objective and subjective task performance. A key takeaway for designers is that, while current drone sounds are generally perceived as annoying and have a negative influence on surrounding people (e.g., intrusive, irritating), they should not be viewed solely as a nuisance. Instead, drone sound can serve as a rich auditory cue with potential benefits, such as aiding localization, intuitively signaling the drone's state, and even promoting relaxation or focus in certain contexts.

8.5 Methodological Protocol for VR in Human–Drone Proxemics Research

When investigating the best way to use virtual reality (VR) to study human–drone proxemics, our goal was not to resolve the ongoing debate around VR's ecological validity, but rather to propose an approach that leverages the benefits of VR while minimizing its limitations. VR provides an immersive illusion of reality but will never fully replicate the nuances of real-world experiences.

Drawing from the literature on VR (see section 2.3) and our own research, we argue that a balance between validity and practicality can and should be achieved. We propose a methodological protocol that outlines key steps for effectively employing VR in human–drone proxemic studies. This multi-step approach includes:

1. **Identifying Key Mechanisms** associated with the variables under study: Experimenters should identify on what relies the expected proxemic outcome of their study and their associated cognitive mechanisms. This initial step can be challenging, particularly when proxemic behaviors are not the primary focus of a study. Researchers may lack familiarity with the processes influencing proxemic responses, making interpretation difficult. Our proxemic model (see chapter 7) simplifies this by helping experimenters situate their variables within the broader proxemic process. This provides clarity on which mechanisms precede or follow the variables in question, offering a more structured understanding of proxemic behaviors.

2. **Assessing VR's Impact:** We reflected on how VR technology might influence these processes. Key aspects included sensory perception, immersion and presence. As discussed in section 7.4.1, our proxemic model (see chapter 7) streamlines this evaluation by providing a clear framework for identifying where and how discrepancies may emerge between the virtual environment and real-world interactions. This includes assessing how sensory

inputs are processed, how situational awareness is formed, and whether any cognitive or behavioral adjustments may differ in the designed VR setting compared to a real-world context.

3. **Minimizing VR's Influence:** Researchers are then expected to mitigate VR's potential impact on study outcomes using relevant theoretical or empirical evidence. While this is often case-specific, our default approach—rooted in insights from our literature review (see section 2.3)—was to design simulations that closely mimicked real-world sensory dynamics. This included addressing common VR-specific issues such as distance compression and motor abilities while also enhancing immersion and presence to ensure the virtual environment felt as realistic as possible.

Applying this framework to virtual reality human–drone proxemic studies provides multiple key benefits.

Addressing Ecological Validity The primary aim is to assess how VR may affect study outcomes and to minimize these effects in order to maximize validity. By doing so, experimenters can justify the ecological validity of their work or specify the contexts in which the findings might apply. For example, when using VR with a virtual silent drone, researchers might acknowledge that current results are not directly transferable to real-world settings due to the absence of sound. However, they can argue that the findings remain ecologically valid for future scenarios where drones may operate silently. This approach addresses the common critique regarding whether VR findings accurately reflect real-world phenomena, ensuring results are as contextually transferable as possible within the current state of knowledge.

Transparency This protocol promotes transparency in VR studies, allowing readers to assess the generalizability of findings. Such transparency is crucial as both VR technology and our understanding of its implications continue to evolve, allowing future researchers to assess the relevance and applicability of past findings. By clearly documenting the methodologies and considerations involved in conducted virtual study, we foster a more robust academic dialogue and facilitate the advancement of knowledge in the field.

Generating New Insights Reflecting on how VR impacts the mechanisms under investigation generates new insights into how VR influences participant responses and how these effects can be mitigated, particularly when exploring novel aspects of human–drone proxemics. This contributes to a growing body of knowledge regarding VR's role in human–drone proxemics and informs the development of new strategies to enhance VR research.

Cumulative Efforts For researchers investigating similar mechanisms, this framework provides a foundational base of knowledge that can be reused, ensuring consistency and reliability across studies. Having already applied this protocol to our function-specific studies, other researchers examining similar proxemic functions can refer to our approach to replicate or build upon it, without needing to start from scratch. Likewise, we were able to reuse the work addressing recurring issues found throughout our studies (e.g., distance compression, motor limitations). By offering a standardized approach to understanding VR's impact, this framework promotes methodological consistency while providing empirically tested mitigation techniques to handle common challenges in VR research.

8.6 Implementation Guidelines for VR in Human–Drone Proxemics Research

While our study highlights the advantages of using VR to explore proxemics, and we have discussed its potential and benefits over real-world methods, we have not delved deeply into the practical steps of implementation. For researchers new to virtual reality, particularly those without a strong background in programming or 3D modeling, the prospect of creating a virtual environment, programming interactions, or animating a drone may seem overwhelming. However, as outlined in our literature review section 2.3, VR research tools are now more accessible than ever. With the wide availability of development platforms, 3D modeling software, and free online resources—including tutorials, 3D models, code libraries, and AI tools—getting started with VR is becoming increasingly straightforward.

For those ready to take the plunge and integrate VR into their research toolbox, we offer practical recommendations based on our experience, outlining the best techniques for various aspects of VR human–drone proxemics research. Moreover, all our unity projects will be made available on a dedicated GitHub repositories [56].

8.6.1 **Basic Principles:** Scene, GameObjects, Components, Scripts, and User Inputs

We utilized Unity 3D software [357] to implement our virtual experiments. Unity allows us to arrange virtual objects, known as *gameObjects*, within a digital space called a *scene*. These gameObjects can take the form of 3D or 2D representations of objects, such as a drone or a chair, or serve as abstract entities that facilitate the simulation's functionality, like a GameManager that operates without a visual representation.

Each gameObject can have *scripts* and *components* attached to it. The scripts, written in C#, provide custom instructions that dictate how these objects behave over time or respond to user actions. Components are built-in functions assigned to gameObjects that define their specific properties. For instance, a component may add physical boundaries to an object, make it an audio source within the scene, or assign animations.

Interactions between gameObjects and with users can be programmed by using scripts to interpret *user inputs* through various channels. The most common method is using VR controllers, but we can also incorporate hand gestures, voice commands, or other input types. Essentially, any data collected from the VR headset or connected sensors about the user's actions in the real world can shape interactions within the virtual simulation.

For example, to synchronize the user's movements with the virtual world, we create a gameObject that represents the user's VR headset, which has a camera component attached. This virtual camera receives data from the user's headset and mirrors its real-time movements, allowing users to explore the virtual environment naturally. By adding an audio listener component to this virtual camera, users can also experience sound within the simulation, further enhancing immersion. This alignment between physical and virtual movements supports natural sensorimotor contingencies for perception, significantly enhancing the sense of presence or "being" in the simulation, as explained in section 2.3. Additionally, this data can be saved as metrics for later analysis (e.g., user speed and position).

These basic principles are particularly valuable for human–drone proxemic studies. By implementing virtual drones in these simulations and designing scenarios where participants naturally exhibit proxemic behaviors, we can effectively investigate human–drone spatial relationships. This approach allows for a safe, controlled, and replicable environment, creating a convincing illusion of real-world interactions. Additionally, it avoids the constraints and complexities of physical experiments, such as safety concerns, environmental variability, or technical limitations.

8.6.2 Immersive Virtual/Mixed Environment

Participants in our studies are immersed in either fully virtual or mixed environments, using modern VR headsets (e.g., Meta Quest 3) that offer varying degrees of blending between the virtual and real world. These environments can closely replicate the experimental room or provide entirely new settings, depending on the study's objectives.

Fully Virtual

In fully virtual environments, users are completely cut off from the real world, except perhaps for sounds. GameObjects within the scene are used to construct the virtual environment, representing key elements where the experiment takes place (e.g., rooms, streets, or homes).

In our work, we opted to replicate the physical experimental rooms within the virtual environment. This decision maximized participants' sense of presence, reduced distance compression, and supported confident, natural navigation within the virtual space. To achieve this, we manually measured the real room's dimensions and replicated key elements (e.g., tables, chairs, windows, and doors) using Unity's built-in modeling tools. Additionally, prefabricated 3D models (prefabs) obtained from online libraries were modified to match real-world objects. Although time-consuming, once completed, these virtual replicas are reusable for future studies, offering long-term benefits.

A critical step in fully virtual environments is aligning the user's real-world position with the virtual environment. To do this, the headset's position and orientation must match the virtual camera's gameObject in the simulation. This synchronization ensures that participants navigate the virtual room as they would the physical space, preventing collisions with unseen real-world objects. Synchronization is achieved by positioning the user in the real world to match the virtual camera's location and orientation, then resetting the position via the VR controller.

When experimenters need to immerse participants in settings beyond the experimental room, although it may raise additional considerations regarding VR's potential impact on proxemic behavior, they can either design custom virtual environments or use assets from the Unity Asset Store. Pre-made environments like homes, streets, or warehouses streamline the setup.

Mixed Environment

Another promising approach we employed is leveraging the mixed-reality features available in modern headsets (e.g., Meta Quest 3). This approach renders the real world through the headset's front-facing cameras while overlaying virtual GameObjects in the scene. Although similar to augmented reality, we consider this "mixed reality" because participants perceive the real world solely through the headset, rather than with their naked eyes.

Mixed reality significantly simplifies the experimental environment setup, allowing experiments to take place in any real-world setting without the need for a fully modeled virtual environment. For instance, a study can be conducted in the lab, then easily adapted for a demonstration at a conference without needing to replicate the conference venue in VR. Moreover, mixed reality offers the potential to test the impact of different environments by simply moving the study to a new physical location, rather than creating new digital environments. This method also opens the possibility for home-based experiments, such as testing domestic drones in participants' homes—something impractical with fully virtual environments.

Similar to fully virtual environments, the level of fidelity can vary based on how much of the real world is overlaid with virtual elements. However, one trade-off of mixed reality is that it offers less control over the participant's experience compared to fully virtual environments. For example, distractions like a window showing foot traffic could impact the experiment. Fortunately, experimenters can address such issues by selectively occluding or modifying real-world elements in the mixed reality view.

Ultimately, we recommend using mixed reality when possible, as it addresses several challenges associated with virtual spaces, facilitates deployment, and is likely to become the preferred method in future research.

8.6.3 Drone Design

For the virtual drone to create a convincing illusion of reality and foster natural perception and reactions, it is crucial that it both looks and behaves in a plausible and realistic manner. This encompasses several key aspects, including the drone's visual appearance, movements, and dynamic sound.

Drone 3D Model

Creating a drone model from scratch can be challenging without experience in 3D modeling, though advancements in AI are rapidly making this process more accessible. For researchers without 3D modeling expertise, there are numerous online resources offering high-quality drone models, both free and paid. Websites such as TurboSquid, Sketchfab, and the Unity Asset Store provide models of existing drones or futuristic designs that can be modified for research purposes. When selecting a model, ensure that it has separable components for later animation (such as propellers). Then it can simply be integrated in Unity as a gameObject, be further modified if needed, such as adding components to its as we did in chapter 3 with the digital facial expressions, or attach scripts to control its behaviour and responses to user's actions.

Drone Movements

To effectively control drone movements, we recommend that experimenters first observe real drones in flight. Pay attention to their imperfect motions and constant adjustments while stationary, as well as their smooth, straight movements characterized by natural speed increases and deceleration. Notice how they lean forward or backward to accelerate or decelerate and the behavior of their rotating propellers. All these factors contribute to the distinctive appearance of a flying drone and must be integrated into the animation to ensure that its behavior appears intuitively plausible and physically realistic, rather than computer-generated.

For small deviations from target points, experimenters can utilize Unity's built-in animation system effectively. However, this approach has limitations for the primary movements. After testing the built-in Unity animation system, we found it to be too constrained and complex for fine-tuning, limiting flexibility. We also experimented with lerp techniques, which offer greater flexibility but can appear physically unrealistic if not finely adjusted. Ultimately, we found that using a PID (Proportional-Integral-Derivative) controller provided the most convincing results. This method is easy to implement and allows for fine-tuning through well-defined parameters.

A detailed article on how to use this technique in Unity can be found here [363], and its application is illustrated in the study presented in chapter 6, with the Unity project made available on a dedicated GitHub repository [56].

By employing this technique, experimenters can make a drone transition smoothly from one point to another, mimicking realistic flying behavior. This approach is highly flexible and can be adapted to various flying patterns, allowing the drone to respond dynamically to environmental changes and user inputs—capabilities that are not achievable with standard animations.

Drone Sound

The sound of a drone is a critical component of its presence and serves as an expected cue alongside its visual appearance. Thus, replicating this sound within the simulation is essential for maximizing the illusion of realism. In our work, we utilized an audio sample sourced from a drone sound test video [375] and adjusted the pitch to closely match the drones we were using (either the Parrot AR2.0 or the DJI Tello), for which we had comparative audio data. We specifically selected a relatively long sample that could be seamlessly looped (available on GitHub [56]).

We spatialized the audio using Unity's 3D sound engine, designating the drone object as the sound source (via the Audio Source component) and the participants' VR headsets as receivers (via the Audio Listener component). The sound intensity was dynamically adjusted based on the distance between the drone and the participants, utilizing the 3D Sound Settings of the Audio Source component. Additionally, the audio balance shifted between the left and right channels according to the participants' orientation relative to the drone. This setup aimed to create a more immersive auditory experience, closely mimicking the presence of a real drone.

To further enhance realism, we implemented slight sound modifications, such as pitch changes through the Audio Source component, based on the drone's movement to indicate speed variations, reflecting increased propeller rotation. This aspect was fine-tuned through careful observations of real drones. In Unity, sound intensity can be easily controlled, either directly through the audio component or via an attached script. For true-to-life simulations, experimenters should explore various sound levels to find those that accurately represent a real drone's presence.

In transformed simulations, experimenters can customize the drone sound as needed—for instance, to minimize its impact, allowing other drone components to influence participants, as demonstrated in the second study presented in chapter 3. Additionally, sound intensity can be manipulated to specifically examine its effects, as illustrated in chapter 6.

Airflow

Drones are often associated with the airflow generated by their propellers. In our simulations, we did not address the replication of this element, and therefore cannot recommend specific methods for simulating them. While it might be feasible to use a fan to replicate the airflow, synchronizing it with the virtual drone's movements would be complex and could complicate the VR experience—something we aim to present as an easy-to-deploy method. Nonetheless, we could imagine a setting using mixed reality setting, with a stationary virtual drone at the location of a small fan on which a location sensor could be attached to make sure it matches its position. The virtual augmented object would hide the real fan resulting in virtual drone with produced airflow. Future works could look into that but it suggest constrained scenarios and more complex setting than simply putting on the VR headset and synchronising uers real and virutal positions.

In more complex experimental scenarios, unless the airflow is a key component of the mechanisms being examined, we recommend not attempting to replicate this aspect of drone behavior. However, it is important to acknowledge its absence in the simulation and to reflect on how this omission might impact the results.

8.6.4 Data Collection

A key advantage of using VR for human–drone proxemic research is the ability to collect accurate and detailed metrics throughout the experiment, and the data collection process in Unity is relatively straightforward.

In our VR simulations, each *gameObject* is associated with various variables, such as its position and orientation in the virtual environment. These variables are derived from built-in Unity components as well as custom C# scripts. By leveraging Unity's frame-by-frame data access, experimenters can track these variables over time. Since the time interval between frames is known, this data provides reliable temporal information about each object's movements and interactions, even though it is constrained by the frame rate (frames per second).

To implement data collection, experimenters can write custom C# scripts that access these variables at each frame or at specific events (e.g., when the participant interacts with a drone or crosses a certain boundary). These scripts can then write the collected data to .txt files, including essential metrics like participant ID and experimental conditions. The data can be saved at any point, such as when the application closes, and stored directly on the VR headset. Post-experiment, researchers can retrieve the data by connecting the headset to a computer and transferring the saved files for further analysis.

It is advisable to maintain a consistent structure for these files, as it simplifies subsequent analysis using tools like R or Python. For instance, storing the data in a CSV format, with columns for time, position, orientation, and event markers, allows for streamlined analysis and visualization.

In addition to tracking positional data, we integrated interactive 2D *gameObjects* into the VR simulation for real-time questionnaires, allowing participants to provide subjective feedback (e.g., user experience, comfort levels) during the experiment. This in-simulation data collection complements the quantitative metrics and can be easily reused for future studies, as demonstrated in chapter 5 and chapter 6. For more advanced studies, recent VR headsets with eye-tracking features can further enhance data collection by capturing metrics such as pupil size, fixation points, and fixation duration, providing valuable insights into visual attention and cognitive workload [291].

Practical examples, including available code and resources, can be accessed on our GitHub, which hosts our Unity Projects [56].

8.7 Limitations

While the limitations of individual studies have been discussed in the dedicated chapters, we will here consider the broader limitations of our work.

Surface-Level Exploration Although we aimed to provide depth in each examined proxemic function, our objective of presenting a comprehensive framework inevitably resulted in some areas being explored less thoroughly. This breadth-over-depth approach may have left certain aspects underexplored. For example, while social dimensions are often overemphasized in social robotics, we might have underestimated their relevance in the context of drones—especially given the current state of drone design. This leaves room for future studies to focus more on these underexplored aspects.

Hypothetical Framework While our model is grounded in empirical observations and supported by relevant theoretical frameworks, its application to a wide range of external entities—beyond drones—remains hypothetical at this stage. To strengthen the model's validity and generalizability, empirical testing in diverse real-world contexts is essential. Future research should explore how the model performs across different types of agents, including ground robots, and other interactive systems. Such testing will provide the necessary evidence to either validate or refine the framework and enhance its applicability to a broader set of human–agent interactions.

Limited Temporal Scope The metrics collected during our studies predominantly reflect short-term interactions. Consequently, insights gained may not fully capture the dynamics of human–drone relationships over time. Longitudinal studies, perhaps with repeated interactions over weeks or months, would be essential to understanding how these relationships evolve. Such studies could explore how user attitudes and responses change over time as they become more accustomed to drone behaviors.

Technological Limitations While we advocate for the partial validity of VR in studying human–drone proxemics, we acknowledge that this technology has not been rigorously tested in every practical applications. For example, questions remain regarding the effectiveness of current VR headsets in accurately simulating long-distance perception of drones, as their resolution and field of view may impact how users perceive distance and movement.

Chapter 9

Conclusion, Future Research and Final Remarks

9.1 Conclusion

The aim of this thesis was to lay a strong foundation for understanding human–drone proxemics and to establish virtual reality (VR) as a viable tool for studying these interactions. Through this work, we have made significant progress in addressing two key research questions that are pivotal to the future of human–drone interaction.

First, in exploring **Research Question 1** *What motivates individuals' proxemic behaviors around drones and how do they manifest?* we conducted an extensive review of the literature and identified a critical gap in the understanding of human–drone proxemics. Existing research in human–robot interaction was insufficient to explain how drones, as aerial entities, fit into established proxemic models. By identifying four key driving mechanisms of proxemic behavior—defensive, communicative, goal-oriented, and arousal regulation—we provided a structured and theoretically motivated framework for understanding these interactions. Through a series of user studies, we validated these mechanisms and their application to drones, ultimately developing an integrated model of human proxemics with external entities that can guide future research. This model contributes a valuable tool for hypothesis-driven studies, helping researchers predict and explain human spatial behaviors around autonomous agents, including social drones, in varied contexts.

In addressing **Research Question 2** *How best to use VR to study human–drone proxemics?* we examined the potential and limitations of VR as a method for studying human–drone interactions. The use of VR allowed us to simulate complex environments and avoid the practical and safety challenges of real-world drone studies. We systematically examined how each proxemic function might be altered in VR and developed methods to mitigate these effects, ensuring that our findings remained applicable to real-world contexts. Our work provides both practical insights into VR study design and empirically supported guidelines for researchers interested in using VR to explore human–drone proxemics. A key contribution of our work was the development of a methodological protocol that researchers can follow to maximize ecological validity and foster transparency in the use of VR for studying proxemics. Rather than guaranteeing the generalizability of findings, this protocol highlights potential alterations caused by the virtual environment and offers strategies to mitigate them. By doing so, it allows other researchers to critically evaluate the validity of the VR setup in relation to their specific research goals, ensuring they can make informed judgments on the applicability of the findings to real-world settings. By integrating our proxemic framework with this protocol, we simplified the process of identifying where VR might alter specific proxemic mechanisms, thus facilitating more robust and accurate research outcomes.

In sum, this thesis represents the beginning of a longer journey toward understanding how humans and drones will coexist in shared spaces. By developing a solid theoretical and methodological foundation for studying proxemics in human–drone interaction, we hope to have provided valuable tools and insights for future research, ultimately helping to ensure that drones can be designed and deployed in ways that are both effective and respectful of human spatial boundaries.

9.2 Future Research Directions

The aim of our work was to lay a solid foundation for understanding human–drone proxemics and exploring the use of VR to study this phenomenon. Rather than concluding the journey, this research marks its beginning, opening up numerous pathways for future investigation. Some of these potential research directions are outlined below.

9.2.1 Drone Swarms: One for all and all for one

While our work has centered on individual human–drone interactions, envisioning a world where autonomous drones operate as individual entities in one-to-one interactions with humans, research trends are increasingly moving towards a more collective approach—where swarms of drones function as a cohesive unit [19, 26, 80, 188]. These drone swarms, which operate as a single entity, offer new possibilities but also present unique challenges for human interaction and proxemics [178, 325].

The shift towards swarm intelligence raises questions about how human proxemic behavior will evolve when faced not with a singular drone but with an entire swarm acting collectively.

The emergence of swarm drones highlights the importance of understanding proxemic behavior not only in one-to-one interactions but also in multi-entity scenarios. In such cases, the psychological and situational assessment of multiple drones moving in coordination may differ significantly from that of a single drone. Individuals may respond to the swarm as a whole, perceiving it as a unified entity, or they may attempt to negotiate proxemic boundaries with each individual drone. This opens an avenue for future research to explore how human cognitive mechanisms and spatial behavior adapt in these more complex settings.

9.2.2 Beyond Distance: The Territorial Dimension of Space

While proxemics primarily focuses on interpersonal distances, it also extends to the concept of territoriality [163]. Territoriality refers to the control, defense, and use of a space that individuals or groups consider their own. Unlike proxemic spaces, which are largely situational and dynamic, territories are often more fixed, representing areas where individuals have a sense of ownership or belonging.

For example, regardless of the physical distance between a person and a drone, if the drone enters a person's garden, it is likely to trigger territorial behaviors. This reaction stems not just from personal space violations, but from the intrusion into a defined, often private, area that the individual perceives as their territory.

Territoriality varies depending on context and personal relationships. Some spaces, such as a hospital room, may temporarily function as an extension of one's personal space, where territorial behaviors are heightened due to a sense of vulnerability. Sommer's (1969) classic work, Personal Space: The Behavioral Basis of Design [336], highlights various instances of territorial behavior, such as the invasion of a patient's hospital room by medical staff or visitors. As Sommer notes, "Hospital patients complain not only that their personal space and their very bodies are continually violated by nurses, interns, and physicians who do not bother to introduce themselves or explain their activities, but that their territories are violated by well-meaning visitors who ignore 'No Visitors' signs."

These examples underscore the importance of recognizing territories within proxemic frameworks, as they offer insight into how space, ownership, and privacy influence human behavior. Territoriality can apply to a range of environments, from intimate settings like bathrooms, where privacy is paramount, to shared spaces where ownership is less defined but still significant.

9.2.3 Incorporating External Influences

In our work, we have primarily examined the spatial influence of a single external entity on human proxemic behavior. While this approach has provided valuable insights, we have largely disregarded other potential sources of influence, aside from goal-oriented behaviors. However, in real-world scenarios, proxemic behavior often emerges from the complex interplay of forces from multiple sources, not just a single entity. These forces may arise from other people, environmental factors, or surrounding objects—each of which can influence an individual's spatial decisions.

We believe our model can be extended to account for these additional external proxemic influences. Since the model already maps individual dimensions of relevance (e.g., threat perception, social appropriateness), incorporating external sources would follow the same basic principles—evaluating how these factors contribute to proxemic potentials. By doing so, the framework would provide a more comprehensive view of spatial behavior, capturing the complexity of real-world interactions where multiple sources exert influence simultaneously.

That said, while this extension remains a theoretical consideration, it would greatly benefit from dedicated empirical research. Investigating how external forces from various origins interact with proxemic behavior could provide important insights, ultimately helping to refine the model and enhance its practical applicability.

9.2.4 Understand First, Then Interact and Communicate

As outlined in the literature review (see subsection 2.1.2), research on social drones can be grouped into four main axes: understanding their impact on individuals (Understand), developing interaction techniques (Interact), evaluating communication methods for drones (Communicate), and exploring concrete use cases (Apply). Our work clearly falls within the Understand axis, focusing on how drones influence proxemic behaviors in humans.

A logical next step would be to shift focus from understanding proxemics to exploring how drones might use proxemics as a communication channel. Future research could investigate whether drones can leverage spatial behavior to convey information, much like humans use personal space to communicate comfort, intention, or social dynamics. This would open new avenues for studying whether varying drone proxemic behaviors are perceived differently and how those perceptions align with the conceptual lenses developed in this thesis.

For example, if a drone is perceived as a social agent, its proximity to individuals could be interpreted in a social context—potentially signaling approachability, dominance, or submission. Conversely, if the drone is viewed more as a functional object, its proxemic behaviors may be understood in terms of pragmatic intentions, such as performing tasks, avoiding obstacles, or optimizing navigation. Exploring these dual perspectives could deepen our understanding of how proxemics may serve as a reliable, non-verbal communication method for drones.

From an interaction standpoint, integrating proxemic awareness into drone technology could provide more intuitive forms of human–drone interaction. By responding naturally to human spatial cues, proxemic-aware drones could align with the vision of ubiquitous computing, in which technology "weaves itself into the fabric of everyday life until it becomes indistinguishable from it" [373]. In this vision, drones would seamlessly integrate into human environments, becoming more perceptive, adaptive, and intuitive to users' behaviors, making the interaction feel as natural as possible [156].

9.2.5 More than a Mirror: a Limitless World

In our work, we used VR as a counterpart to real-world studies, primarily to overcome the numerous limitations inherent in human–drone proxemic research conducted in real environments (see subsection 2.1.3). Since the validity of VR for proxemic studies was still under scrutiny and its impact on proxemic behavior not fully understood, we carefully designed our virtual environments through extensive research and theoretical reflection. Each environment was tailored to the specific mechanisms being investigated, with a strong emphasis on transparency and ecological validity. We devised a methodological protocol to maximize ecological validity, allowing for external evaluation of the simulation process (see subsection 4.6.1). Our conceptualization of proxemics, along with the detailed breakdown of how proxemic behaviors emerge (see chapter 7), enables a clearer identification of where VR might alter these behaviors. This makes it easier to apply the methodological protocol and justify the validity of any given simulation.

With this groundwork in place, we believe researchers should now take a more ambitious approach to VR. Instead of merely replicating real-world settings minus the associated constraints, the full potential of VR should be explored. VR offers opportunities to experiment with interaction techniques, innovative designs, and complex scenarios that are either not yet feasible or too difficult to set up in the real world. Our use of mixed reality in chapter 6 also highlights the rapid pace at which these technologies are evolving, and we should embrace these advancements fully.

Moreover, as VR becomes more popular, novel applications are emerging, such as remote virtual user studies [249], which enable participants to engage in research from their own homes using VR headsets. This trend moves closer to realizing VR's potential in reaching more diverse and representative samples, further expanding its utility for research purposes.

9.3 A Final Thought

9.3.1 The Purpose of Social Drones: A Critical Examination

Throughout this PhD journey, I found myself reflecting not only on the technological advancements we seek to make but also on the broader motivations behind our work. At times, I questioned whether the push for innovation was driven by the genuine need to solve societal problems, or if it was fueled by an inherent pressure to create new technologies simply for the sake of novelty. Drones, for instance, offer clear, tangible benefits in certain contexts—such as medical deliveries to remote or hard-to-reach locations [130], which undeniably serve noble and practical purposes.

However, as we expand the scope of drones into more human-centered domains, like emotional support [124] or companionship [141, 200], it becomes worth asking: why do we feel the need to fill such roles with technology? Are we addressing a genuine gap, or are we bypassing human relationships and solutions that might be better suited to these tasks? If there is indeed a gap, should we address it through technology, or would it be more prudent to confront the underlying issues directly?

As mentioned in the introduction (see chapter 1), technology and society co-evolve, transitioning from raw concepts to seamlessly integrated devices. Social drones exemplify this progression as a potentially transformative technology still in its early stages of development. This raises a critical question: once drones are fully integrated into our world, what kind of society will emerge, and how will this technology shape the way we live?

In our quest to improve quality of life, we often equate "better" with "easier." We strive to develop technologies that simplify tasks, streamline processes, and reduce effort. While this drive is understandable, I believe it presents a paradox. By making life easier, we risk fostering dependence on technology to the point where we erode people's ability to engage with fundamental aspects of being human. Technologies are increasingly taking over tasks that define our daily lives—whether it's emotional regulation, physical movement, or simple activities like cleaning and interacting with our environment. These tasks are not mere inconveniences to be eliminated; they are part of what shapes our identities, gives us purpose, and offers a balance between effort and joy. Life's challenges, whether emotional, physical, or practical, play a crucial role in our personal growth. By delegating them to technology, we risk diminishing the experiences that teach resilience, problem-solving, and self-sufficiency.

Thus, while technological progress is inevitable and often beneficial, we must carefully consider what we are trading off in this pursuit of convenience. Are we, in our quest to make life easier, potentially making it less meaningful? The work we do in fields like human–drone interaction opens exciting avenues, but it should be grounded in a deeper understanding of the human experience, ensuring that the technology we create enhances our lives without undermining the very things that make us human.

Appendix A

Appendix - Chapter 3

Participant Information Sheet and Consent Form Study #1

HDI Experiment

Participant Information sheet

IMPORTANT – Exclusion criteria

To take part in this study, you must meet the following requirements:

1. Aged 16 or over
2. No history (personal and family) of epileptic seizures, strokes, or photosensitivity
3. Not a member of any of the following groups
    a. Pregnant women
    b. The elderly
    c. Sufferers of any serious medical conditions i.e. you fall into one of the following categories i. Inpatient care
        ii. Incapacity
        iii. Chronic serious health conditions iv. Permanent or long term conditions
        v. Conditions requiring multiple treatments
    d. Sleep deprived
    e. Under the influence of alcohol
    f. Previously suffered concussion or traumatic brain injury
    g. Prone to dizziness from immersive virtual experiences
    h. Sufferers of panic attacks or generalised anxiety disorders which might be provoked by wearing headphones / being unable to hear your surroundings
    i. Prone to issues with balance or motor function (i.e. you can walk around a room over the course of an hour).
4. Be comfortable with wearing a head-mounted display (HMD) such as an Oculus Quest 2.

1. Invitation

You are being invited to take voluntarily part in a research experiment. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

Thank you for reading this.

2. Purpose of the User Study

We would like to reach out to you to participate in a paid study examining how users interact with an autonomous drone in the lab. Your participation is voluntary, and you are free to withdraw at any time, without giving any reason, and you are free to omit answering any question without providing a reason. The analysis of this experiment will be published at top-tier venues such as CHI, the premier international conference of Human-Computer Interaction, IEEE VR. All publications are fully anonymised and findings and specific measurements cannot be traced back to you.

3. What will happen to me if I take part?

You will be fitted with a virtual reality headset such that it sits comfortably on your head, and you can hear correctly. This will occur in the room SAWB 422 of the Sir Alwyn Williams Building of the School of Computing Science, at the University of Glasgow. After filling a questionnaire to assess your perception of a drone, you are tasked to interact with it in virtual reality. Beforehand we will explain you the procedure to follow and introduce you to the drone and the different voice commands you will be able to perform within the virtual environment. Once the interaction has been performed, you will be asked to fill in a questionnaire which measure your sense of presence. We will also add some individual questions to collect additional qualitative data about your experience and perception when interacting with the drone.

During the study, we are going to record the graphical representation of the entire virtual environment. This includes objects within the environment (e.g., the drone) and your movements. For all recordings we will use appropriate file extensions (e.g., .txt) and store them in separate files on our local machine. We will upload the anonymised data (through participant ID's) to the University of Glasgow cloud.

At the end of the study, there will be some additional questions within the context of the experiment. This will be in the form of semi-structured interviews. This helps the research team to better understand the experience you have undertaken. An Amazon voucher (£6 an hour) will be emailed to you within a mounth of participating.

4. Why have I been chosen?

Your participation has been solicited through emails, social media postings, word-of-mouth or notice board postings, to which you replied. Your participation is voluntary, and you are free to withdraw at any time, without giving any reason, and you are free to omit answering any question, without providing a reason.

5. Conditions and Data Storage

All gathered data during the sessions will be stored directly in the University of Glasgow cloud to keep it confidential (https://gla-my.sharepoint.com) or locally. Access to the raw data is restricted to the researcher (Robin Bretin) and his supervisors (Dr Mohamed Khamis, Professor Emily Cross) only. Your data is fully anonymised and there is no way to trace it back to you. The results of the study may appear in a number of published studies, in a confidential format where anonymity is preserved. Based on your agreement we will use the data for scientific papers and/or presentations at conferences.

6. Data Usage

The data will be used within our research and is part of Robin Bretin's Research PhD. We will store the raw data in the University of Glasgow cloud (https://gla-my.sharepoint.com). Access to the raw data is restricted to the researcher (Robin Bretin) and his supervisors (Dr Mohamed Khamis, Professor Emily Cross) only. Based on the request of participants the data can be destroyed at any point. The data will be kept until beyond the end of the Research PhD (up to 10 years) and findings of the experiment might be re-used for additional research projects within Robin's Research PhD.

7. Personal Data

Some personal data will be stored and may be presented as part of scientific communications. We want you to be aware of which data will be collected and how we intend to use them.

Your signature will only be recorded on a detachable supplemental sheet with the consent information, which will be kept separate and secure in a locked office. We use IDs to cover participant's identity.

Your email is required for us to arrange the experiment date and send you useful information. It will not be used for anything else and will not be shown to any other person than the experimenter. Your age, gender, origin, previous experience with drones, previous experience with virtual reality will also be collected in a demographic questionnaire. The option "prefer not to say" is available for the gender. The information from the demographic questionnaire will be used in the statistical analysis for explorative purposes and to enrich the comprehension of our future results. If the dataset will be published as part of scientific communications, this will be done in an anonymized fashion.

Finally, we will record your voice during the post experiment interview. It is recorded so that the experimenter can work on it after the experiment. A transcript of the interview will be made and its content may be used as part of scientific communication, but the record of your voice will never be played. If the dataset will be published as part of scientific communications, this will be done in an anonymized fashion.

8. Who has reviewed the study?

This study adheres to the BPS ethical guidelines and has been approved by the College of Science and Engineering ethics committee of The University of Glasgow (ref: [300210015]).

9. Funding and Contact

This research is supported by the University of Glasgow and the Social AI CDT.

The project has been reviewed and approved by the Research Ethics Committee in the School of Computing Science at the University of Glasgow. For further information please feel free to get in touch with the researcher xxxxxxx@student.gla.ac.uk.

Whilst you are free to discuss your participation in this study with the researcher, if you would like to speak to someone not involved in the study, you may contact the Ethics Committee at Christoph.Scheepers@glasgow.ac.uk.

Data Protection and Confidentiality

Your data will be processed in accordance with the Data Protection Act 1998 (up until 24th May 2018) and the General Data Protection Regulation 2016 (GDPR) thereafter. All information collected about you will be kept strictly confidential. Unless they are anonymised in our records, your data will be referred to by a unique participant number rather than by name. If you consent to being audio recorded, all recordings will be destroyed once they have been transcribed. Your data will only be viewed by the researcher/research team. All electronic data will be stored on a password-protected computer file within the School of Computing Science. All paper records will be stored in a locked filing cabinet within the School of Computing Science. Your consent information will be kept separately from your responses in order to minimise risk in the event of a data breach.

Data Protection Rights
University of Glasgow is a Data Controller for the information you provide. You have the right to access information held about you.

Your right of access can be exercised in accordance with the Data Protection Act 1998 (up until 24th May 2018) and the General Data Protection Regulation thereafter. You also have other rights including rights of correction, erasure, objection, and data portability. For more details, including the right to lodge a complaint with the Information Commissioner's Office, please visit www.ico.org.uk. Questions, comments and requests about your personal data can also be sent to the University Data Protection Officer - dp@gla.ac.uk (https://www.gla.ac.uk/myglasgow/dpfoioffice/contact/)

Thank you for volunteering to take part in this study. If there are any questions or issues, or if you wish to receive a summary of the findings of this experiment later, please feel free to get in touch with the researcher at any time.

Experimenter
Robin Bretin
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Supervisors

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Title of Project:	Human drone interaction
Experimenter details: **Supervisors details:**	Robin Bretin (xxxxxxxx@student.gla.ac.uk) Mohamed Khamis (mohamed.khamis@glasgow.ac.uk) Emily Cross (emily.cross@glasgow.ac.uk)
Participant Id:	

Before agreeing to this consent form, you should have been given an information sheet to read, which outlines exclusion criteria and explains the general purpose of this experiment and the tasks it involves. Please tick the box after each statement to indicate that you have read and understand the statement, and that you agree with it.

CONSENT FORM	Please initial box
I confirm that I have read and understood the Participant Information Sheet and understand my Data Protection Rights under GPDR for the above study and have had the opportunity to ask questions.	☐
I have had the opportunity to think about the information and ask questions and understand the answers I have been given.	☐
I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, without my legal rights being affected.	☐
I give consent for my actions to be recorded during the study	☐
I understand that all data collected from me will be treated confidentially and anonymized, will be seen in its raw form only by the experimenters, and if published will not be identifiable as coming from me.	☐
I agree that my name, contact details and data described in the information sheet will be kept for the purposes of this research project.	☐
I agree that the researchers are allowed to archive all data taken during the experiment in online repositories such as Enlighten: Research Data: http://researchdata.gla.ac.uk/. I am aware of the fact that I can get in touch with the researchers at any time to demand the deletion or retrieval of these recordings.	☐
I agree to my interview being audio-recorded.	☐

I understand that my information and things that I say in an interview be quoted in reports and articles that are published about the study, but my name or anything else that could tell people who I am will not be revealed.	☐
I agree to take part in the study.	☐

This study has been approved by the Ethics Committee (300210015).

By signing this form, you have read the conditions stated above and agree to take part in the study.

Date *Signature*

Researcher *Date* *Signature*

(1 copy for participant; 1 copy for researcher)

Summary Statistics

Table A.1: Summary Statistics of the minimum distance grouped by Height and Framing. The mean varies between each condition of the two variables.

Height	Social	N	Mean(cm)	Sd(cm)
Above_Eyes	Social	23.00	99.10	49.00
Below_Eyes	Social	23.00	122.70	30.10
Eye_Level	Social	23.00	111.90	40.10
Above_Eyes	Technical	22.00	85.80	39.80
Below_Eyes	Technical	22.00	106.40	22.20
Eye_Level	Technical	22.00	97.70	26.30

Table A.2: Summary statistics of the minimum distance for each Framing condition. The average minimum distance is higher for the Social framing. Each participant provided three measurements, corresponding to the three height conditions, resulting in a total of 69 measurements for the Social framing and 66 measurements for the Technical framing.

Social	N	Mean(cm)	Sd(cm)
Social	69.00	111.30	41.00
Technical	66.00	96.60	31.10

Table A.3: Summary statistics of the minimum distance for each Height. The average minimum distance decreases as the Height increases.

Height	N	Mean(cm)	Sd(cm)
Above_Eyes	45.00	92.60	44.80
Below_Eyes	45.00	114.70	27.50
Eye_Level	45.00	105.00	34.40

Cover Stories

Social Framing - "Happy"

Let me introduce you to our Social Autonomous Drone, which makes SAD for an acronym, hence we name him Happy! Happy is a social robot which means its purpose is to interact with people to collaborate or assist them in their daily life or for more specific tasks (i.e., assist firefighters to reach tricky spots, personal flying assistant, help rescue teams to locate injured people, guide joggers during their runs or provide a comforting presence for elder people). But as a guide dog was once a clumsy puppy, Happy is not ready for the field yet and has a lot to learn. In this experiment I will observe Happy while you perform a task in the environment. As a dog knows “sit”, “come”, and “Fetch!”, Happy is able to understand “Happy, look for my keys”, and “Happy, Land”.

A bit of context.

Basically, imagine you are at home, and you ask Happy to look for your keys, so it requires him to fly in a stationary position (meaning he does not move from its location). At the same time, you want to do something in the room which requires you to cross the room (i.e., reach the button at the other end of the room to switch the light on). You will have to move within the place while Happy is busy flying, looking for your keys. It is this kind of situation we want to replicate here.

Before the detailed protocol is explained, could you please answer the short questionnaire that you will discover by clicking on next? Keep in mind that there is no wrong answer, only your opinion matters.

Technical Framing

The AR 2.0 ® drone is a quadrotor unmanned aerial vehicle (UAV). Taking advantage of its onboard camera and rounded propeller guards, it can be used for indoor or outdoor leisure flying and aerial shots. Initially remotely controlled using a smartphone or a tablet, we have developed a machine learning based flying system, which basically learns through practice how to fly around people within inhabited environments. The drone's behavioural system is built using a deep reinforcement learning approach. It combines the use of an artificial neural network and reinforcement learning. Based on a set of conditions, the optimal action of the drone is approximated and associated with a computed expected reward. In this experiment I will observe the drone while you perform a task in the environment. Currently, the AR 2.0 is able to understand "Drone, look for my keys", and "Drone, land".

A bit of context.

Basically, imagine you are at home, and you ask the drone to look for your keys, so it requires it to fly in a stationary position (meaning it does not move from its location). At the same time, you want to do something in the room which requires you to cross the room (i.e., reach the button at the other end of the room to switch the light on). You will have to move within the place while the drone is flying and performing a task. It is this kind of situation we want to replicate here.

Before the detailed protocol is explained, could you please answer the short questionnaire that you will discover by clicking on next? Keep in mind that there is no wrong answer, only your opinion matters.

Description of Drones

Word Cloud of the adjectives used to describe drones (Left) and applications people were aware of (Right). The size indicates the term's frequency (e.g., $f_{Fast} = 14$, $f_{Useful} = 9$, $f_{Noisy} = 6$). Seventy-two persons answered the demographic questionnaire providing the data for these charts. From these individuals, 45 then participated to the user study.

Participant Protocol

The only difference between the technical and social protocol is that in one case we refer to the drone as “The drone" and in the other case as “Happy".

Protocol - Social

You understand that both you and Happy will have to achieve something in parallel. So first, to initiate Happy's task, you will ask him to search for your keys by saying “Happy, look for my keys". You will then perform your own task and once it's done, you will end Happy's task by saying “Happy, land”. Now, what about your task? You may have noticed that papers of colour are located on the walls and on the table next to your initial position. When Happy will take off (after your vocal command), a sequence of colours will appear on the paper located on the table behind you. Your task is to reach and touch the papers of colour in the same order as the sequence. So, if you read “1. Red, 2. Purple, 3. Black”, you will have to reach the red paper first, then the purple and finally the black one. It is important that you respect the colours and the order. Once you did it, you can go back to your initial position. And as your task is over, you can ask Happy to land by saying “Happy, Land". You will repeat this procedure three times. Meaning that once your assistant has landed, you will ask again “Happy, look for my keys”, a new sequence of colours will appear, and you know what to do next. While you move in the room just let Happy focus on its task while you focus on yours.

Protocol Shematic - Social

Interview Guide Sheet

As the interview was conducted in a semi-directed format, it's important to note that not all the questions listed in this guide sheet were necessarily asked during the interview. Follow-up questions, which might not be included here, were posed as the conversation naturally evolved. Additionally, the phrasing of questions may have varied, and there was no strict adherence to a chronological order in presenting them.

Cultural Background
… So, I see you grew up in [INSERT WORLD REGION]. Do you think your perception of the drone and the way you interacted with it may have been shaped or at least influenced by your culture?
Drone perception
If you remember the Pre-study Questionnaire, there was a question where you had to select some adjectives to describe the drones you had encountered before… I see that you used: [INSERT ADJECTIVES]. Why did these adjectives come to your mind when thinking about drones? … Would you change these adjectives based on the interaction you just performed? … What is your opinion about [“Happy”/The AR 2.0]? … What do you think of its appearance (size, form, color)/ the way it flies / the sound it makes? … If you could change something about these different aspects, what would it be? … Why? … Do you think that if we presented you the drone in a more [social/technical] way, it would have changed your perception and the way you interacted with it? --- *Then give the other presentation and ask again.*
Drone uses
When presenting the drone, we evoked some uses but nothing very clear. **Personal Drone** If you had a personal autonomous drone, how would you use it? What tasks would you want it to perform? … So more an [inside/outside] drone? … How do you picture yourself interacting with it? … Would you speak to him, touch it, gesture, control it remotely? … … What could make you reject it? … Would you prefer a tool of something closer to a living being? … How would you feel about using it next to people that you don’t know? … How would you feel if someone that you don't know is using their drone next to you? **Public Drone** … Now if we think of a drone that could be used by public organizations rather than individuals, for instance firefighters, delivery companies, etc., how should they be used in your opinion? … What would be your main concerns knowing there are public drones flying around? How would you feel about it? **…** Do you think the design of public and private drones should be different?
Physical perception
Now let’s focus on your experience during the experiment. … Where was your attention focused during the different steps of the experiment? … How did you feel when approaching the drone? … In your opinion, what were the main elements of the environment that made you behave the way you did? On the contrary, what was unimportant?
Virtual reality
I see you are [not/well/very well] familiar with Virtual reality. The use of this tool for research is one of our main research axes, so your feedback is precious. … How would you describe the virtual environment you were immersed in? … To which extent did you believe the drone was real? Did you think the drone could touch you? … Compared to a real-world environment, what do you think was missing to make it more compelling? … Do you think you would have behaved the same way in a real-world experiment with a real drone? Why?

Participant Information Sheet and Consent Form Study #2

Social Drone

Participant Information sheet

IMPORTANT – Exclusion criteria

To take part in this study, you must meet the following requirements:

1. Aged 18 or over
2. No history (personal and family) of epileptic seizures, strokes, or photosensitivity
3. Not a member of any of the following groups
    a. Pregnant women
    b. The elderly
    c. Sufferers of any serious medical conditions i.e. you fall into one of the following categories i. Inpatient care
        ii. Incapacity
        iii. Chronic serious health conditions iv. Permanent or long term conditions
        v. Conditions requiring multiple treatments
    d. Sleep deprived
    e. Under the influence of alcohol
    f. Previously suffered concussion or traumatic brain injury
    g. Prone to dizziness from immersive virtual experiences
    h. Sufferers of panic attacks or generalised anxiety disorders which might be provoked by wearing headphones / being unable to hear your surroundings
    i. Prone to issues with balance or motor function (i.e. you can walk around a room over the course of an hour).
4. Be comfortable with wearing a head-mounted display (HMD) such as an Oculus Quest 2.

1. Invitation

You are being invited to take voluntarily part in a research experiment. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

Thank you for reading this.

2. Purpose of the User Study

We would like to reach out to you to participate in a study examining how users naturally evolve near a social drone drone in the lab. Your participation is voluntary, and you are free to withdraw at any time, without giving any reason, and you are free to omit answering any question without providing a reason. The analysis of this experiment will be published at top-tier venues such as CHI, the premier international conference of Human-Computer Interaction, HRI. All publications are fully anonymised and findings and specific measurements cannot be traced back to you.

3. What will happen to me if I take part?

The experiment will take place in the Media Lab of the at the Chalmers University of Technology. You will be fitted with a virtual reality headset such that it sits comfortably on your head, and you can hear correctly. Within the virtual environment, you will perform tasks and interact with the drone in a shared space. Once you completed your tasks, you will be asked to fill some questionnaires. The whole experiment should last 45 minutes maximum.

During the study, we are going to record the graphical representation of the entire virtual environment. This includes objects within the environment (e.g., the drone) and your movements. For all recordings we will use appropriate file extensions (e.g., .txt) and store them in separate files on our local machine. We will upload the anonymised data (through participant ID's) to the University of Glasgow cloud.

4. Why have I been chosen?

Your participation has been solicited through emails, social media postings, word-of-mouth or notice board postings, to which you replied. Your participation is voluntary, and you are free to withdraw at any time, without giving any reason, and you are free to omit answering any question, without providing a reason.

5. Conditions and Data Storage

All gathered data during the sessions will be stored directly in the University of Glasgow cloud to keep it confidential (https://gla-my.sharepoint.com) or locally. Access to the raw data is restricted to the researcher (Robin Bretin) and his supervisors (Dr Mohamed Khamis, Professor Emily Cross) only. Your data is fully anonymised and there is no way to trace it back to you. The results of the study may appear in a number of published studies, in a confidential format where anonymity is preserved. Based on your agreement we will use the data for scientific papers and/or presentations at conferences.

6. Data Usage

The data will be used within our research and is part of Robin Bretin's Research PhD. We will store the raw data in the University of Glasgow cloud (https://gla-my.sharepoint.com). Access to the raw data is restricted to the researcher (Robin Bretin) and his supervisors (Dr Mohamed Khamis, Professor Emily Cross) only. Based on the request of participants the data can be destroyed at any point. The data will be kept until beyond the end of the Research PhD (up to 10 years) and findings of the experiment might be re-used for additional research projects within Robin's Research PhD.

7. Personal Data

Some personal data will be stored and may be presented as part of scientific communications. We want you to be aware of which data will be collected and how we intend to use them.

Your signature will only be recorded on a detachable supplemental sheet with the consent information, which will be kept separate and secure in a locked office. We use IDs to cover participant's identity.

Your email is required for us to arrange the experiment date and send you useful information. It will not be used for anything else and will not be shown to any other person than the experimenter.

Your age, gender, origin, previous experience with drones, previous experience with virtual reality will also be collected in a demographic questionnaire. The option “prefer not to say” is available for the gender. The information from the demographic questionnaire will be used in the statistical analysis for explorative purposes and to enrich the comprehension of our future results. If the dataset will be published as part of scientific communications, this will be done in an anonymized fashion.

8. Who has reviewed the study?

This study adheres to the BPS ethical guidelines and has been approved by the College of Science and Engineering ethics committee of The University of Glasgow (ref: [300220159]).

9. Funding and Contact

This research is supported by the University of Glasgow and the Social AI CDT.

The project has been reviewed and approved by the Research Ethics Committee in the School of Computing Science at the University of Glasgow. For further information please feel free to get in touch with the researcher r.bretin.1@research.gla.ac.uk.

Whilst you are free to discuss your participation in this study with the researcher, if you would like to speak to someone not involved in the study, you may contact the Ethics Committee at Christoph.Scheepers@glasgow.ac.uk.

Data Protection and Confidentiality

Your data will be processed in accordance with the Data Protection Act 1998 (up until 24th May 2018) and the General Data Protection Regulation 2016 (GDPR) thereafter. All information collected about you will be kept strictly confidential. Unless they are anonymised in our records, your data will be referred to by a unique participant number rather than by name. If you consent to being audio recorded, all recordings will be destroyed once they have been transcribed. Your data will only be viewed by the researcher/research team. All electronic data will be stored on a password-protected computer file within the School of Computing Science. All paper records will be stored in a locked filing cabinet within the School of Computing Science. Your consent information will be kept separately from your responses in order to minimise risk in the event of a data breach.

Data Protection Rights

University of Glasgow is a Data Controller for the information you provide. You have the right to access information held about you.

Your right of access can be exercised in accordance with the Data Protection Act 1998 (up until 24th May 2018) and the General Data Protection Regulation thereafter. You also have other rights including rights of correction, erasure, objection, and data portability. For more details, including the right to lodge a complaint with the Information Commissioner’s Office, please visit www.ico.org.uk. Questions, comments and requests about your personal data can also be sent to the University Data Protection Officer - dp@gla.ac.uk (https://www.gla.ac.uk/myglasgow/dpfoioffice/contact/)

Thank you for volunteering to take part in this study. If there are any questions or issues, or if you wish to receive a summary of the findings of this experiment later, please feel free to get in touch with the researcher at any time.

Experimenter
Robin Bretin
r.bretin.1@research.gla.ac.uk

Supervisors

- Dr. Mohammad Obaid
  mobaid@chalmers.se
- Dr. Mohamed Khamis
  Mohamed.Khamis@glasgow.ac.uk

- Emily Cross
  Emily.cross@glasgow.ac.uk

Title of Project: Social Drone

Experimenter details: Robin Bretin (r.bretin.1@research.gla.ac.uk)

Supervisors details: Mohammad Obaid (mobaid@chalmers.se)
Mohamed Khamis (mohamed.khamis@glasgow.ac.uk)
Emily Cross (emily.cross@glasgow.ac.uk)

Participant Id:

Before agreeing to this consent form, you should have been given an information sheet to read, which outlines exclusion criteria and explains the general purpose of this experiment and the tasks it involves. Please tick the box after each statement to indicate that you have read and understand the statement, and that you agree with it.

CONSENT FORM	Please tick box
I confirm that I have read and understood the Participant Information Sheet and understand my Data Protection Rights under GPDR for the above study and have had the opportunity to ask questions.	☐
I have had the opportunity to think about the information and ask questions and understand the answers I have been given.	☐
I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, without my legal rights being affected.	☐
I give consent for my actions to be recorded during the study	☐
I understand that all data collected from me will be treated confidentially and anonymized, will be seen in its raw form only by the experimenters, and if published will not be identifiable as coming from me.	☐
I agree that my name, contact details and data described in the information sheet will be kept for the purposes of this research project.	☐
I agree that the researchers are allowed to archive all data taken during the experiment in online repositories such as Enlighten: Research Data: http://researchdata.gla.ac.uk/. I am aware of the fact that I can get in	☐

touch with the researchers at any time to demand the deletion or retrieval of these recordings.	
I agree to take part in the study.	☐

This study has been approved by the Ethics Committee (300220159).

By signing this form, you have read the conditions stated above and agree to take part in the study.

______________ __________________________

Date *Signature*

_________________________________ _________________________ ______________

Researcher *Date* *Signature*

(1 copy for participant; 1 copy for researcher)

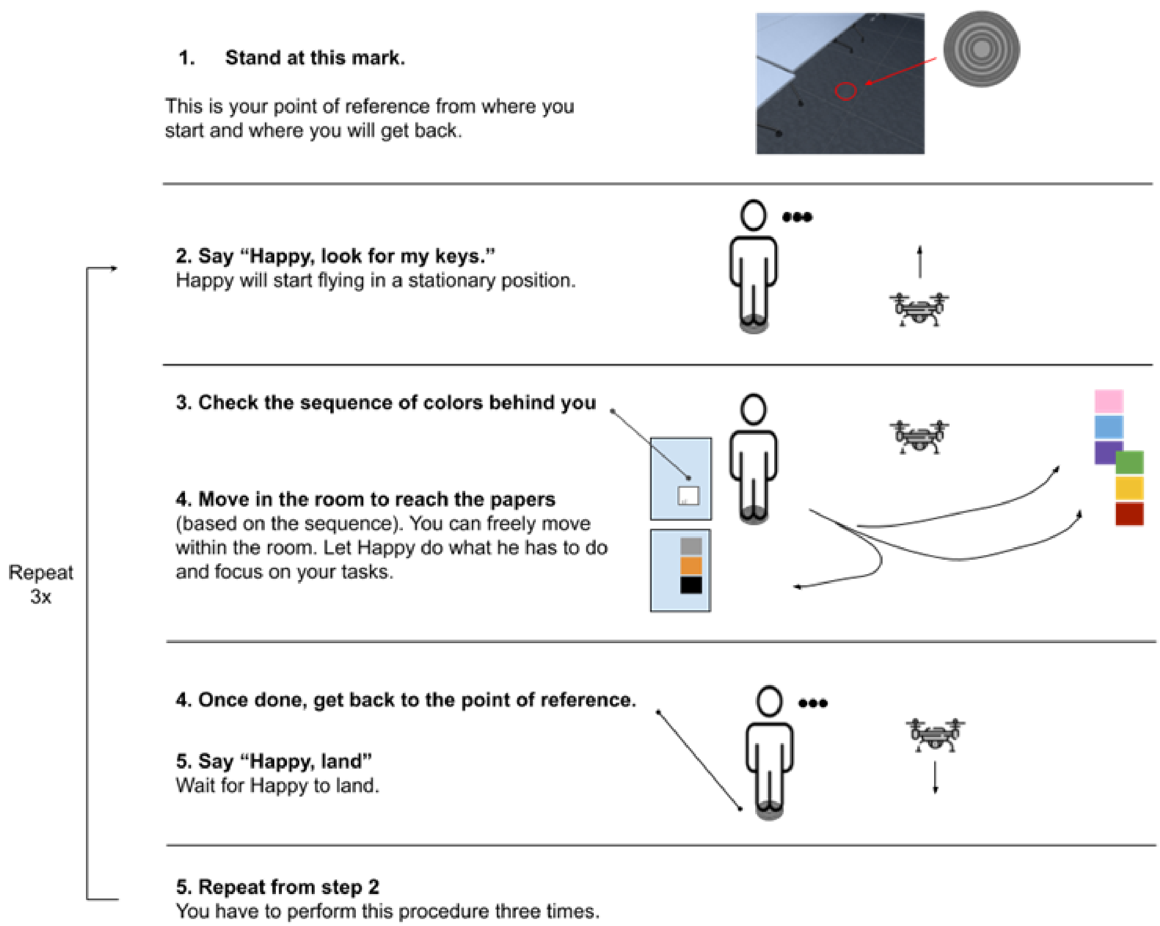

Figure A.1: Participant protocol shematic for the social cover story.

Appendix B

Appendix Chapter 4

Participant Information Sheet and Consent Form Study #3

Participant Information sheet

Human-Drone Interaction Experiment

IMPORTANT – Exclusion criteria

To take part in this study, you must meet the following requirements:

1. Aged 16 or over
2. No history (personal and family) of epileptic seizures, strokes, or photosensitivity
3. Not a member of any of the following groups
   a. Pregnant women
   b. The elderly
   c. Sufferers of any serious medical conditions i.e., you fall into one of the following categories i. Inpatient cares
      ii. Incapacity
      iii. Chronic serious health conditions iv. Permanent or long-term conditions
      v. Conditions requiring multiple treatments
   d. Sleep deprived
   e. Under the influence of alcohol
   f. Previously suffered concussion or traumatic brain injury
   g. Prone to dizziness from immersive virtual experiences
   h. Sufferers of panic attacks or generalised anxiety disorders
   i. Prone to issues with balance or motor function (i.e., you can walk around a room over the course of an hour).
4. Be comfortable with wearing a head-mounted display (HMD) such as an Oculus Quest 2.

1. Invitation

You are being invited to take voluntarily part in a research experiment. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether you wish to take part.

Thank you for reading this.

2. Purpose of the User Study

We would like to reach out to you to participate in a paid study examining how users physiologically react to a drone in the lab. Your participation is voluntary, and you are free to withdraw at any time, without giving any reason, and you are free to omit answering any question without providing a reason. The analysis of this experiment will be published at top-tier venues such as CHI, the premier international conference of Human-Computer Interaction, IEEE VR. All publications are fully anonymised and findings and specific measurements cannot be traced back to you.

3. What will happen to me if I take part?

The experiment takes place in the room SAWB 422 of the Sir Alwyn Williams Building of the School of Computing Science, at the University of Glasgow.

Depending on which group you have been assigned to, you might perform the experiment in a real environment or in an immersive virtual environment. Hence you might be fitted with a virtual reality headset (Oculus Quest 2). In both environments, you will be equipped with mobile sensors to collect physiological data (Electrocardiogram, Electrodermal activity). In addition, you will have to perform a stop-approach procedure which is used to estimate the minimum comfortable distance above which you start feeling discomfort regarding an approaching person or in this case, a drone. Finally, you will be asked to answer some questions throughout the experiment. We will upload the anonymised data (via participant ID's) to the University of Glasgow cloud.

The approximate total duration is 30 minutes. An Amazon voucher (£6 an hour) will be emailed to you within a few days after participating.

4. Why have I been chosen?

Your participation has been solicited through emails, social media postings, word-of-mouth or notice board postings, to which you replied. Your participation is voluntary, and you are free to withdraw at any time, without giving any reason, and you are free to omit answering any question, without providing a reason.

5. Conditions and Data Storage

All gathered data during the sessions will be stored directly in the University of Glasgow cloud to keep it confidential (https://gla-my.sharepoint.com) or locally. Access to the raw data is restricted to the researcher (Robin Bretin) and his supervisors (Dr Mohamed Khamis, Professor Emily Cross) only. Your data is fully anonymised and there is no way to trace it back to you. The results of the study may appear in a few published studies, in a confidential format where anonymity is preserved. Based on your agreement we will use the data for scientific papers and/or presentations at conferences.

6. Data Usage

The data will be used within our research and is part of Robin Bretin's Research PhD. We will store the raw data in the University of Glasgow cloud (https://gla-my.sharepoint.com). Access to the raw data is restricted to the researcher (Robin Bretin) and his supervisors (Dr Mohamed Khamis, Professor Emily Cross) only. Based on the request of participants the data can be destroyed at any point. The data will be kept until beyond the end of the Research PhD (up to 10 years) and findings of the experiment might be re-used for additional research projects within Robin's Research PhD.

7. Personal Data

Some personal data will be stored and may be presented as part of scientific communications. We want you to be aware of which data will be collected and how we intend to use them.

Your signature will only be recorded on a detachable supplemental sheet with the consent information, which will be kept separate and secure in a locked office. We use IDs to cover participant's identity.

Your email is required for us to arrange the experiment date and send you useful information. It will not be used for anything else and will not be shown to any other person than the experimenter. Your age, gender, previous experience with drones, previous experience with virtual reality will also be collected in a demographic questionnaire. The option “prefer not to say” is available for the gender. The information from the questionnaires will be used in the statistical analysis for explorative purposes and to enrich the comprehension of our future results. If the dataset will be published as part of scientific communications, this will be done in an anonymized fashion.

Finally, all physiological data initially stored locally on the experimenter’s computer and an android device will be transferred on a safe hard drive for the duration of the statistical analysis. Then it will be stored in the University of Glasgow Cloud which access is restricted to the research team only and the local data will be deleted. These data will only be used to verify the research hypothesis. No additional analysis will be performed. Results may be presented in conferences and papers, but this will be done in an anonymized fashion. If you wish for your anonymised data to not be included on an online repository, you can explicitly opt out in the consent form.

8. Who has reviewed the study?

This study adheres to the BPS ethical guidelines and has been approved by the College of Science and Engineering ethics committee of The University of Glasgow (ref: [300210260]).

9. Funding and Contact

This research is supported by the University of Glasgow and the Social AI CDT.

The project has been reviewed and approved by the Research Ethics Committee in the School of Computing Science at the University of Glasgow. For further information please feel free to get in touch with the researcher r.bretin.1@research.gla.ac.uk

Whilst you are free to discuss your participation in this study with the researcher, if you would like to speak to someone not involved in the study, you may contact the Ethics Committee at Christoph.Scheepers@glasgow.ac.uk.

Data Protection and Confidentiality

Your data will be processed in accordance with the Data Protection Act 1998 (up until 24th May 2018) and the General Data Protection Regulation 2016 (GDPR) thereafter. All information collected about you will be kept strictly confidential. Unless they are anonymised in our records, your data will be referred to by a unique participant number rather than by name. If you consent to being audio recorded, all recordings will be destroyed once they have been transcribed. Your data will only be viewed by the
researcher/research team. All electronic data will be stored on a password-protected computer file within the School of Computing Science. All paper records will be stored in a locked filing cabinet within the School of Computing Science. Your consent information will be kept separately from your responses to minimise risk in the event of a data breach.

Data Protection Rights

University of Glasgow is a Data Controller for the information you provide. You have the right to access information held about you.

Your right of access can be exercised in accordance with the Data Protection Act 1998 (up until 24th May 2018) and the General Data Protection Regulation thereafter. You also have other rights including rights of correction, erasure, objection, and data portability. For more details, including the right to lodge a complaint with the Information Commissioner’s Office, please visit www.ico.org.uk. Questions, comments and requests about your personal data can also be sent to the University Data Protection Officer - dp@gla.ac.uk (https://www.gla.ac.uk/myglasgow/dpfoioffice/contact/)

Thank you for volunteering to take part in this study. If there are any questions or issues, or if you wish to receive a summary of the findings of this experiment later, please feel free to get in touch with the researcher at any time.

Experimenter
Robin Bretin
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Supervisors

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  Mohamed.Khamis@glasgow.ac.uk
  Tel: +44 (0) 1413308078
- Emily Cross
  Emily.cross@glasgow.ac.uk

Title of Project:	Human drone interaction
Experimenter details:	Robin Bretin (r.bretin.1@research.gla.ac.uk)
Supervisors' details:	Mohamed Khamis (mohamed.khamis@glasgow.ac.uk)
	Emily Cross (emily.cross@glasgow.ac.uk)
Participant Id:	

Before agreeing to this consent form, you should have been given an information sheet to read, which outlines exclusion criteria and explains the general purpose of this experiment and the tasks it involves. Please tick the box after each statement to indicate that you have read and understand the statement, and that you agree with it.

CONSENT FORM	Please initial box
I confirm that I have read and understood the Participant Information Sheet and understand my Data Protection Rights under GPDR for the above study and have had the opportunity to ask questions.	☐
I have had the opportunity to think about the information, ask questions, and understand the answers I have been given.	☐
I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, without my legal rights being affected.	☐
I give consent for my actions to be recorded during the study	☐
I understand that all data collected from me will be treated confidentially and anonymized, will be seen in its raw form only by the experimenters, and if published will not be identifiable as coming from me.	☐
I agree that my name, contact details and data described in the information sheet will be kept for the purposes of this research project.	☐
I agree that the researchers are allowed to archive all data taken during the experiment in online repositories such as Enlighten: Research Data: http://researchdata.gla.ac.uk/. I know I can contact the researchers at any time to demand the deletion or retrieval of these recordings.	☐
I agree to my interview being audio-recorded.	☐

I understand that my information and things that I say in an interview be quoted in reports and articles that are published about the study, but my name or anything else that could tell people who I am will not be revealed.	☐
I agree to take part in the study.	☐

This study has been approved by the Ethics Committee (300210260).

By signing this form, you have read the conditions stated above and agree to take part in the study.

Date ______________ *Signature* ______________________

______________________ ______________ ______________________

Researcher *Date* *Signature*

(1 copy for participant; 1 copy for researcher)

Summary Statistics

Direct comparison of Real-world and Virtual-Reality measures.

This table presents a direct comparison of measures between the real-world and virtual-reality experimental settings. The measures are defined in the Measure subsection of the Method section in the paper. The table includes means, and statistical tests conducted to assess the differences between the two settings. No significant differences were found between the real and virtual experimental settings.

Measure	Variables	Real-World	Virtual Reality	Environment difference
Perceived Stress	*Baseline*	1.35	1.17	**Kruskal-Wallis H test**
	Static Far	1.89	2.64	$\chi2(1) = 0.000691$, $p = 0.979$.
	Approach (0.25 m/s)	4	4.39	No statistically significant difference
	Approach (1 m/s)	4.74	4.61	between the real and virtual environment.
	Static Close	3.39	4.14	
	Resting	1.52	1.5	
	Overall	**2.5**	**2.79**	
Perceived Threat	*0.25 m/s*	3.76	3.56	**Kruskal-Wallis H test**
	1 m/s	3.86	4.28	$\chi2(1) = 0.00168$, $p = 0.967$
	Overall	**3.81**	**3.92**	No statistically significant difference between the real and virtual environment.
Discomfort Level	*40 cm*	41	47.2	**Kruskal-Wallis H test**
	83 cm	19.8	32.3	$\chi2(1) = 1.04$, $p = 0.308$
	120 cm	13.4	25.5	No statistically significant difference
	240 cm	9.59	20.9	between the real and virtual environment.
	360 cm	8.11	19	
	450 cm	6.59	14	
	Overall	**16.5**	**26.5**	
Distance Rating	*40 cm*	-51.5	-54.4	**Kruskal-Wallis H test**
	83 cm	-18	-25.5	$\chi2(1) = 0.0118$, $p = 0.913$
	120 cm	-1.59	-10.4	No statistically significant difference
	240 cm	17.8	13.1	between the real and virtual environment.
	360 cm	34.7	35.5	
	450 cm	48.9	55.2	
	Overall	**4.87**	**2.38**	

Friedman Test for Perceived Stress differences between phases in each environment group, with bonferroni correction for multiple comparisons.

Environment	n	statistic	df	p.value	Kendall's W effect size
Real	23	51.1	4	2.09e-10	0.556 (large)
Virtual	18	53.1	4	8.25e-11	0.737 (large)

Comparison	Environment	p value adjusted	Significance
Baseline vs Static Far	Real	0.496	ns
	Virtual	0.025	*
Baseline vs Approach	Real	0.000941	***
	Virtual	0.000308	**
Baseline vs Static Close	Real	0.05	ns
	Virtual	0.000472	**
Baseline vs Resting	Real	1	ns
	Virtual	0.341	ns
Static Far vs Approach	Real	0.000607	***
	Virtual	0.003	*
Static Far vs Static Close	Real	0.077	ns
	Virtual	0.004	*
Static Far vs Resting	Real	1	ns
	Virtual	0.014	ns
Approach vs Static Close	Real	0.028	*
	Virtual	0.228	ns
Approach vs Resting	Real	0.000613	***
	Virtual	0.000471	**
Static Close vs Resting	Real	0.015	*
	Virtual	0.00031	**

Friedman Test for Discomfort levels and Distance ratings Differences Between Stop distances in Each Environment Group, with Bonferroni Correction for Multiple Comparisons.

Measure	Environment	n	statistic	df	p.value	Kendall's W effect size
Discomfort	Real	22	70.3	5	9.09e-14	0.639 (large)
	Virtual	18	65.4	5	9.15e-13	0.727 (large)
Distance Ratings	Real	22	104	5	6.49e-21	0.948 (large)
	Virtual	18	89.1	5	1.05e-17	0.990 (large)

Comparison	Measure	Environment	p value adjusted	Significance
40 cm vs 83 cm	Discomfort	Real	0.001	**
		Virtual	0.013	*
	Distance Ratings	Real	0.000633	***
		Virtual	0.003	**
40 cm vs 120 cm	Discomfort	Real	0.001	**
		Virtual	0.007	**
	Distance Ratings	Real	0.000644	***
		Virtual	0.003	**
40 cm vs 240 cm	Discomfort	Real	0.002	**
		Virtual	0.007	**
	Distance Ratings	Real	0.000639	***
		Virtual	0.003	**
40 cm vs 360 cm	Discomfort	Real	0.004	**
		Virtual	0.007	**
	Distance Ratings	Real	0.000640	***
		Virtual	0.003	**
40 cm vs 450 cm	Discomfort	Real	0.006	**
		Virtual	0.007	**
	Distance Ratings	Real	0.000640	***
		Virtual	0.003	**
83 cm vs 120 cm	Discomfort	Real	0.007	**
		Virtual	0.013	*
	Distance Ratings	Real	0.001	**
		Virtual	0.007	**
83 cm vs 240 cm	Discomfort	Real	0.062	ns
		Virtual	0.011	*
	Distance Ratings	Real	0.000947	***
		Virtual	0.003	**
83 cm vs 360 cm	Discomfort	Real	0.072	ns
		Virtual	0.007	**
	Distance Ratings	Real	0.000948	***
		Virtual	0.003	**
83 cm vs 450 cm	Discomfort	Real	0.078	ns
		Virtual	0.016	*
	Distance Ratings	Real	0.000956	***
		Virtual	0.003	**
120 cm vs 240 cm	Discomfort	Real	0.444	ns
		Virtual	0.412	ns
	Distance Ratings	Real	0.003	**
		Virtual	0.003	**
120 cm vs 360 cm	Discomfort	Real	0.444	ns
		Virtual	0.141	ns
	Distance Ratings	Real	0.001	**
		Virtual	0.003	**
120 cm vs 450 cm	Discomfort	Real	0.444	ns
		Virtual	0.160	ns
	Distance Ratings	Real	0.001	**
		Virtual	0.003	**
240 cm vs 360 cm	Discomfort	Real	0.444	ns
		Virtual	1	ns
	Distance Ratings	Real	0.003	**
		Virtual	0.005	**
240 cm vs 450 cm	Discomfort	Real	0.444	ns
		Virtual	0.414	ns
	Distance Ratings	Real	0.003	**
		Virtual	0.005	**
360 cm vs 450 cm	Discomfort	Real	0.444	ns
		Virtual	1	ns
	Distance Ratings	Real	0.007	**
		Virtual	0.007	**

Appendix C

Appendix Chapter 5

Participant Information Sheet and Consent Form Study #4

HDI Experiment

Participant Information sheet

IMPORTANT – Exclusion criteria

To take part in this study, you must meet the following requirements:

1. Aged 16 or over
2. No history (personal and family) of epileptic seizures, strokes, or photosensitivity
3. Not a member of any of the following groups
   a. Pregnant women
   b. The elderly
   c. Sufferers of any serious medical conditions i.e. you fall into one of the following categories i. Inpatient care
      ii. Incapacity
      iii. Chronic serious health conditions iv. Permanent or long term conditions
      v. Conditions requiring multiple treatments
   d. Sleep deprived
   e. Under the influence of alcohol
   f. Previously suffered concussion or traumatic brain injury
   g. Prone to dizziness from immersive virtual experiences
   h. Sufferers of panic attacks or generalised anxiety disorders which might be provoked by wearing headphones / being unable to hear your surroundings
   i. Prone to issues with balance or motor function (i.e. you can walk around a room over the course of an hour).
   j. Serious difficulties to focus.
4. Be comfortable with wearing a head-mounted display (HMD) such as an Oculus Quest 2.

1. Invitation

You are being invited to take voluntarily part in a research experiment. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part. Thank you for reading this.

2. Purpose of the User Study

We would like to reach out to you to participate in a paid study examining how users naturally evolve near an autonomous drone in the lab. Your participation is voluntary, and you are free to withdraw at any time, without giving any reason, and you are free to omit answering any question without providing a reason. The analysis of this experiment will be published at top-tier venues such as CHI, the premier international conference of Human-Computer Interaction, IEEE VR. All publications are fully anonymised and findings and specific measurements cannot be traced back to you.

3. What will happen to me if I take part?

The experiment will take place in the room SAWB 422 of the Sir Alwyn Williams Building of the School of Computing Science, at the University of Glasgow. You will be fitted with a virtual reality headset such that it sits comfortably on your head, and you can hear correctly. Within the virtual environment, both you and the drone will perform tasks independently in a shared space. Once you completed your tasks, you will be asked to fill some questionnaires. We will end the experiment with a short semi-directed interview (15 minutes), and the whole experiment should last 45 minutes. An Amazon voucher (£10 an hour) will be emailed to you shortly after your participation.

During the study, we are going to record the graphical representation of the entire virtual environment. This includes objects within the environment (e.g., the drone) and your movements. For all recordings we will use appropriate file extensions (e.g., .txt) and store them in separate files on our local machine. We will upload the anonymised data (through participant ID's) to the University of Glasgow cloud.

4. Why have I been chosen?

Your participation has been solicited through emails, social media postings, word-of-mouth or notice board postings, to which you replied. Your participation is voluntary, and you are free to withdraw at any time, without giving any reason, and you are free to omit answering any question, without providing a reason.

5. Conditions and Data Storage

All gathered data during the sessions will be stored directly in the University of Glasgow cloud to keep it confidential (https://gla-my.sharepoint.com) or locally. Access to the raw data is restricted to the researcher (Robin Bretin) and his supervisors (Dr Mohamed Khamis, Professor Emily Cross) only. Your data is fully anonymised and there is no way to trace it back to you. The results of the study may appear in a number of published studies, in a confidential format where anonymity is preserved. Based on your agreement we will use the data for scientific papers and/or presentations at conferences.

6. Data Usage

The data will be used within our research and is part of Robin Bretin's Research PhD. We will store the raw data in the University of Glasgow cloud (https://gla-my.sharepoint.com). Access to the raw data is restricted to the researcher (Robin Bretin) and his supervisors (Dr Mohamed Khamis, Professor Emily Cross) only. Based on the request of participants the data can be destroyed at any point. The data will be kept until beyond the end of the Research PhD (up to 10 years) and findings of the experiment might be re-used for additional research projects within Robin's Research PhD.

7. Personal Data

Some personal data will be stored and may be presented as part of scientific communications. We want you to be aware of which data will be collected and how we intend to use them.

Your signature will only be recorded on a detachable supplemental sheet with the consent information, which will be kept separate and secure in a locked office. We use IDs to cover participant's identity.

Your email is required for us to arrange the experiment date and send you useful information. It will not be used for anything else and will not be shown to any other person than the experimenter. Your age, gender, origin, previous experience with drones, previous experience with virtual reality will also be collected in a demographic questionnaire. The option "prefer not to say" is available for the gender. The information from the demographic questionnaire will be used in the statistical analysis for explorative purposes and to enrich the comprehension of our future results. If the dataset will be published as part of scientific communications, this will be done in an anonymized fashion.

Finally, we will record your voice during the post experiment interview. It is recorded so that the experimenter can work on it after the experiment. A transcript of the interview will be made and its content may be used as part of scientific communication, but the record of your voice will never be played. If the dataset will be published as part of scientific communications, this will be done in an anonymized fashion.

8. Who has reviewed the study?

This study adheres to the BPS ethical guidelines and has been approved by the College of Science and Engineering ethics committee of The University of Glasgow (ref: [300220100]).

9. Funding and Contact

This research is supported by the University of Glasgow and the Social AI CDT.

The project has been reviewed and approved by the Research Ethics Committee in the School of Computing Science at the University of Glasgow. For further information please feel free to get in touch with the researcher r.bretin.1@research.gla.ac.uk.

Whilst you are free to discuss your participation in this study with the researcher, if you would like to speak to someone not involved in the study, you may contact the Ethics Committee at Christoph.Scheepers@glasgow.ac.uk.

Data Protection and Confidentiality

Your data will be processed in accordance with the Data Protection Act 1998 (up until 24th May 2018) and the General Data Protection Regulation 2016 (GDPR) thereafter. All information collected about you will be kept strictly confidential. Unless they are anonymised in our records, your data will be referred to by a unique participant number rather than by name. If you consent to being audio recorded, all recordings will be destroyed once they have been transcribed. Your data will only be viewed by the researcher/research team. All electronic data will be stored on a password-protected computer file within the School of Computing Science. All paper records will be stored in a locked filing cabinet within the School of Computing Science. Your consent information will be kept separately from your responses in order to minimise risk in the event of a data breach.

Data Protection Rights

University of Glasgow is a Data Controller for the information you provide. You have the right to access information held about you.

Your right of access can be exercised in accordance with the Data Protection Act 1998 (up until 24th May 2018) and the General Data Protection Regulation thereafter. You also have other rights including rights of correction, erasure, objection, and data portability. For more details, including the right to lodge a complaint with the Information Commissioner's Office, please visit www.ico.org.uk. Questions, comments and requests about your personal data can also be sent to the University Data Protection Officer - dp@gla.ac.uk (https://www.gla.ac.uk/myglasgow/dpfoioffice/contact/)

Thank you for volunteering to take part in this study. If there are any questions or issues, or if you wish to receive a summary of the findings of this experiment later, please feel free to get in touch with the researcher at any time.

Experimenter
Robin Bretin
r.bretin.1@research.gla.ac.uk

Supervisors

- Dr. Mohamed Khamis
  Mohamed.Khamis@glasgow.ac.uk
- Emily Cross
  Emily.cross@glasgow.ac.uk

Title of Project:	Human drone interaction
Experimenter details:	Robin Bretin (r.bretin.1@research.gla.ac.uk)
Supervisors details:	Mohamed Khamis (mohamed.khamis@glasgow.ac.uk)
	Emily Cross (emily.cross@glasgow.ac.uk)
Participant Id:	

Before agreeing to this consent form, you should have been given an information sheet to read, which outlines exclusion criteria and explains the general purpose of this experiment and the tasks it involves. Please tick the box after each statement to indicate that you have read and understand the statement, and that you agree with it.

CONSENT FORM	Please initial box
I confirm that I have read and understood the Participant Information Sheet and understand my Data Protection Rights under GPDR for the above study and have had the opportunity to ask questions.	☐
I have had the opportunity to think about the information and ask questions and understand the answers I have been given.	☐
I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, without my legal rights being affected.	☐
I give consent for my actions to be recorded during the study	☐
I understand that all data collected from me will be treated confidentially and anonymized, will be seen in its raw form only by the experimenters, and if published will not be identifiable as coming from me.	☐
I agree that my name, contact details and data described in the information sheet will be kept for the purposes of this research project.	☐
I agree that the researchers are allowed to archive all data taken during the experiment in online repositories such as Enlighten: Research Data: http://researchdata.gla.ac.uk/. I am aware of the fact that I can get in touch with the researchers at any time to demand the deletion or retrieval of these recordings.	☐
I agree to my interview being audio-recorded.	☐

I understand that my information and things that I say in an interview be quoted in reports and articles that are published about the study, but my name or anything else that could tell people who I am will not be revealed.	☐
I agree to take part in the study.	☐

This study has been approved by the Ethics Committee (300220100).

By signing this form, you have read the conditions stated above and agree to take part in the study.

_______________ _______________________

Date *Signature*

_____________________________ _______________ _______________________

Researcher *Date* *Signature*

(1 copy for participant; 1 copy for researcher)

Interview Guide Sheet

As the interview was conducted in a semi-directed format, it's important to note that not all the questions listed in this guide sheet were necessarily asked during the interview. Follow-up questions, which might not be included here, were posed as the conversation naturally evolved. Additionally, the phrasing of questions may have varied, and there was no strict adherence to a chronological order in presenting them.

Semi-directed post-study explorative Interview

Impact of the task

…

You did the same task in two different situations. We're curious to know if you noticed any differences between them.

…

Behavioral Differences: Did you behave differently in the two situations? Can you share what you did differently and why?

…

Emotional Responses: Did your feelings change during the task? How did your emotions differ between the relaxed and competitive situations?

…

Perception of the Drone: How did you see the drone when you were tidying your room compared to the competitive setting? Did this change how you acted?

…

Visual Attention: Where did you mainly focus your attention during the task? Did this change between the relaxed and competitive situations?

…

Thought Process: What were you thinking about while doing the task? Did your thoughts change between tidying your room and the competitive setting?

…

Handling Explosive Boxes: How did the red explosive boxes affect what you did? Were you more careful or strategic when the drone carried these boxes? Did the situation change how you viewed the red boxes?

…

Collocated work

Paying Attention to the Drone: During the study, how much did you focus on the drone? Were there any specific moments or things about it that grabbed your attention more?

…

Concerns with the Drone: Did you have any worries or thoughts while working with the drone? Was there anything that made you feel uneasy?

…

Feelings Near the Drone: How did you feel when moving around and getting close to the drone, especially when it was moving? Did those feelings change during the task?

…

Working with Drones in the Future: What do you think might stop or help people and drones work together in the future? Are there any specific things that come to mind?

…

Enhancing Collocated Experience: Thinking about the drone in the study, what changes could enhance the overall experience of working in parallel with a drone, both in terms of comfort and performance?

…

Virtual reality

…

Real-World vs. VR Behavior: Do you believe your behavior in the virtual environment would mirror your actions in a real-world experiment with a physical drone? What factors might influence any differences?

…

Appendix D

Appendix Chapter 6

Participant Information Sheet and Consent Form Study #5

Human—Drone Study

Participant Information sheet

<u>IMPORTANT – Exclusion criteria</u>

To take part in this study, you must meet the following requirements:

- Aged 16 or over
- No history (personal and family) of epileptic seizures, strokes, or photosensitivity
- Not a member of any of the following groups
  - Pregnant women
  - The elderly
  - Sufferers of any serious medical conditions i.e. you fall into one of the following categories: inpatient care, incapacity, chronic serious health conditions, permanent or long-term conditions, conditions requiring multiple treatments.
  - Sleep deprived
  - Under the influence of alcohol
  - Previously suffered concussion or traumatic brain injury
  - Prone to dizziness from immersive virtual experiences
  - Sufferers of panic attacks or generalised anxiety disorders which might be provoked by wearing headphones / being unable to hear your surroundings
  - Prone to issues with balance or motor function (i.e. you can walk around a room over the course of an hour).
- Be comfortable with wearing a head-mounted display (HMD) such as an Meta Quest 3.
- No auditory impairment.

1. Invitation

You are being invited to take voluntarily part in a research experiment. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part. Thank you for reading this.

2. Purpose of the User Study

We would like to reach out to you to participate in a paid study examining how users naturally evolve near an autonomous drone in the lab. Your participation is voluntary, and you are free to withdraw at any time, without giving any reason, and you are free to omit answering any question without providing a reason. The analysis of this experiment will be published at top-tier venues such as CHI, the premier international conference of Human-Computer Interaction, IEEE VR. All publications are fully anonymised and findings and specific measurements cannot be traced back to you.

3. What will happen to me if I take part?

The experiment will take place in the XR Room of the Advanced Research Center, at the University of Glasgow. You will be fitted with a virtual reality headset such that it sits comfortably on your head, and you can hear correctly. Through this headset, you will have a clear view of the real-world environment, augmented only by the presence of a virtual drone. You will engage in a task while a drone operates in front of you, and you will be asked to provide ratings on various scales to assess your experience.

The experiment will end with a short semi-directed interview (10 minutes), and the whole experiment will last 50 minutes maximum. An Amazon voucher (£10) will be emailed to you shortly after your participation.

4. Why have I been chosen?

Your participation has been solicited through emails, social media postings, word-of-mouth or notice board postings, to which you replied. Your participation is voluntary, and you are free to withdraw at any time, without giving any reason, and you are free to omit answering any question, without providing a reason.

5. Conditions and Data Storage

All gathered data during the sessions will be stored directly in the University of Glasgow cloud to keep it confidential (https://gla-my.sharepoint.com) or locally. Access to the raw data is restricted to the researcher (Robin Bretin) and his supervisors (Dr Mohamed Khamis, Professor Emily Cross) only.

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Your signature will only be recorded on a detachable supplemental sheet with the consent information, which will be kept separate and secure in a locked office. We use IDs to cover participant's identity.

Your email is required for us to arrange the experiment date and send you useful information. It will not be used for anything else and will not be shown to any other person than the experimenter.

Your age, gender, origin, previous experience with drones, previous experience with virtual reality will also be collected in a demographic questionnaire. The option “prefer not to say” is available for the gender. The information from the demographic questionnaire will be used in the statistical analysis for explorative purposes and to enrich the comprehension of our future results. If the dataset will be published as part of scientific communications, this will be done in an anonymized fashion.

Finally, we will record your voice during the post experiment interview. It is recorded so that the experimenter can work on it after the experiment. A transcript of the interview will be made and its content may be used as part of scientific communication, but the record of your voice will never be played. If the dataset will be published as part of scientific communications, this will be done in an anonymized fashion.

8. Who has reviewed the study?

This study adheres to the BPS ethical guidelines and has been approved by the College of Science and Engineering ethics committee of The University of Glasgow (ref: [300230169]).

9. Funding and Contact

This research is supported by the University of Glasgow and the Social AI CDT.

The project has been reviewed and approved by the Research Ethics Committee in the School of Computing Science at the University of Glasgow. For further information please feel free to get in touch with the researcher r.bretin.1@research.gla.ac.uk.

Whilst you are free to discuss your participation in this study with the researcher, if you would like to speak to someone not involved in the study, you may contact the Ethics Committee at Christoph.Scheepers@glasgow.ac.uk.

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Your right of access can be exercised in accordance with the Data Protection Act 1998 (up until 24th May 2018) and the General Data Protection Regulation thereafter. You also have other rights including rights of correction, erasure, objection, and data portability. For more details, including the right to lodge a complaint with the Information Commissioner’s Office, please visit www.ico.org.uk. Questions, comments and requests about your personal data can also be sent to the University Data Protection Officer - dp@gla.ac.uk (https://www.gla.ac.uk/myglasgow/dpfoioffice/contact/)

Thank you for volunteering to take part in this study. If there are any questions or issues, or if you wish to receive a summary of the findings of this experiment later, please feel free to get in touch with the researcher at any time.

Experimenter
Robin Bretin
r.bretin.1@research.gla.ac.uk

Supervisors
- Dr. Mohamed Khamis
  Mohamed.Khamis@glasgow.ac.uk
- Emily Cross
  Emily.cross@glasgow.ac.uk

Title of Project: Human drone interaction

Experimenter details: Robin Bretin (r.bretin.1@research.gla.ac.uk)

Supervisors details: Mohamed Khamis (mohamed.khamis@glasgow.ac.uk)

Emily Cross (emily.cross@glasgow.ac.uk)

Participant Id:

Before agreeing to this consent form, you should have been given an information sheet to read, which outlines exclusion criteria and explains the general purpose of this experiment and the tasks it involves. Please tick the box after each statement to indicate that you have read and understand the statement, and that you agree with it.

CONSENT FORM	Please initial box
I confirm that I have read and understood the Participant Information Sheet and understand my Data Protection Rights under GPDR for the above study and have had the opportunity to ask questions.	
I have had the opportunity to think about the information and ask questions and understand the answers I have been given.	
I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, without my legal rights being affected.	
I give consent for my actions to be recorded during the study	
I understand that all data collected from me will be treated confidentially and anonymized, will be seen in its raw form only by the experimenters, and if published will not be identifiable as coming from me.	
I agree that my name, contact details and data described in the information sheet will be kept for the purposes of this research project.	
I agree that the researchers are allowed to archive all data taken during the experiment in online repositories such as Enlighten: Research Data: http://researchdata.gla.ac.uk/. I am aware of the fact that I can get in touch with the researchers at any time to demand the deletion or retrieval of these recordings.	
I agree to my interview being audio-recorded.	

I understand that my information and things that I say in an interview be quoted in reports and articles that are published about the study, but my name or anything else that could tell people who I am will not be revealed.	☐
I agree to take part in the study.	☐

This study has been approved by the Ethics Committee (300230169).

By signing this form, you have read the conditions stated above and agree to take part in the study.

Date *Signature*

Researcher *Date* *Signature*

(1 copy for participant; 1 copy for researcher)

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