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Investigating Emotionally Resonant Vibrations as a Calming Intervention for People with Social Anxiety

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Abstract

Social anxiety is a prevalent mental health concern and its adverse effects impact quality of life. Exposure Therapy is a key component of prominent psychotherapies for social anxiety, but adherence can be challenging and an intervention improving retention and accessibility would be valuable. Vibrotactile stimulation is a potential intervention for *in vivo* exposure as it can discreetly augment other objects or wearable devices during a social situation without interrupting conversation. This thesis explored the development of a calming vibrotactile intervention for social anxiety exposure therapy, prioritising the experiences of socially anxious users to inform the design and display of novel stimuli. As vibrotactile stimuli have a narrow affective range, novel emotionally resonant stimuli, which evoke real world sensations to elicit an associated emotional response (e.g. stimuli that evoke cat purring to remind users of past animal touch), were studied as an avenue to deliver calming experiences. Five studies and two surveys were conducted. Results from the first two experiments showed emotional responses to stimuli varied between participants, depending individual associations with real-world phenomena. Along with two surveys, this informed the investigation of the specific requirements and affective haptic preferences of socially anxious users. User suggestions and affective preferences from these surveys informed the testing of a wider selection of emotionally resonant cues in the third experiment, trialed alongside warm and cool thermal cues to observe impact on emotional resonance and response, although the effects were too minor to justify their future use. With a library of emotionally resonant stimuli validated, methods of delivering them to users was explored with participatory prototyping. Participants who reported high levels of social anxiety designed personalised comfort objects, then augmented them with stimuli. These designs informed the design of three prototype objects which were augmented with vibrations in a final between-groups study which assessed if they could reduce anxiety during a social exposure task. Participants in the treatment group held their choice of object and stimulus to during exposure and exhibited significantly more varied anxiety responses to the task than a control group, reporting that their objects were calming and helpful. These findings suggest that emotionally resonant vibrotactile cues can act as a calming intervention, but their efficacy requires personalisation and varies strongly per user. This thesis contributes novel understanding of the specific requirements of socially anxious users when interacting with affective haptics and pioneers a new category of calming vibrotactile stimuli, with demonstrable applicability in socially anxious settings.

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Declaration and Contributing Papers

The research presented in this thesis is entirely the author's own work. This thesis exploits the parts of these papers that are directly attributable to the author:

Experiments 1 and 2 in Chapter 3 have been published at ICMI 2020:

> Shaun Alexander Macdonald, Stephen Brewster, and Frank Pollick. 2020. **Eliciting Emotion with Vibrotactile Stimuli Evocative of Real-World Sensations**. In *Proceedings of the 2020 International Conference on Multimodal Interaction (ICMI '20).* Association for Computing Machinery, New York, NY, USA, 125–133. https://doi.org/10.1145/3382507.3418812

Survey 2 in Chapter 4 has been published at ICMI 2021:

> Shaun Alexander Macdonald, Euan Freeman, Stephen Brewster, and Frank Pollick. 2021. **User Preferences for Calming Affective Haptic Stimuli in Social Settings.** In *Proceedings of the 2021 International Conference on Multimodal Interaction (ICMI '21).* Association for Computing Machinery, New York, NY, USA, 387–396. https://doi.org/10.1145/3462244.3479903

Experiment 3 in Chapter 3 has been accepted for upcoming publication at ICMI 2022:

> Shaun Alexander Macdonald, Stephen Brewster, and Frank Pollick. 2022. **The Impact of Thermal Cues on Affective Responses to Emotionally Resonant Vibrations** In *Proceedings of the 2022 International Conference on Multimodal Interaction (ICMI '22).* Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3536221.3556572

The participatory prototyping and Experiment 4 in Chapter 5 is currently undergoing revision and re-submission to the ACM journal *Transactions on Human Computer Interaction* under the title *Prototyping and Evaluation of Emotionally Resonant Vibrotactile Comfort Objects as a Calming Social Anxiety Intervention*.

Chapter 1

Introduction

1.1 Motivation

Social anxiety is defined as the fear of scrutiny and negative evaluation during social performance [176] and individuals who experience social anxiety suffer from negative effects that impact quality of life including social isolation, decreased access to public spaces, stigmatisation and mental distress [3, 206, 207]. Social anxiety symptoms can be a vicious cycle, as perceiving one's internal anxiety symptoms, and increased external scrutiny of potential negative judgement by others, can continually worsen one's perception of social competence and further worsen anxiety symptoms [176]. When social anxiety has a clinically significant impact on an individual's social, occupational or other functioning, it is defined as Social Anxiety Disorder (SAD), which is a prominent mental health concern with a lifetime prevalence (the percentage of the population which experiences the condition at some time in their life) of 12% [109]. In addition, social anxiety is also a symptom of, or co-morbid with, several other notable mental health conditions including Traumatic Brain Injury, ADHD and depression [207]. Social anxiety is a challenge faced by many people which negatively impacts their lives, and thus interventions which can reduce the difficulty of living with social anxiety and effect long-term rehabilitation have clear value for people with SAD and many other co-morbid mental health conditions.

The core practical impact of living with social anxiety is that it makes engaging in social exposure a more inaccessible, intimidating and difficult experience, motivating avoidance of such situations. Social exposure is itself a core component of societal human interaction, from socialising with others, to attending shared private and public spaces such as offices, leisure,shopping and healthcare facilities. It is vital to Exposure Therapy (ET), the structured repetition of exposure to the stimuli or scenarios that makes a patient feel anxious or scared, with the aim of helping participants manage their symptoms and adjust maladaptive emotional responses [179]. ET is vital for several prominent psychological interventions for social anxiety with efficacy proven in the decades since research recognised their necessity, including Cognitive Behavioural Therapy and Dialectical Behavioural Therapy [60, 211]. ET itself also has proven efficacy [23, 60], but adherence to this therapy - the act of facing one's fears - can be challenging and is a limitation [173, 203]. HCI research has investigated reducing the difficulty of ET adherence with Virtual Reality Exposure Therapy (VRET), crafting controlled exposure scenarios [51] with the addition of calming stimuli and biofeedback [179]. While effective [149] and valuable, VRET does not address the difficulty of complying with the traditional ET widely used in many psychotherapies. There remains a need for an intervention can be used during *in vivo* social exposure to facilitate emotion regulation and thus make adherence to social exposure and to therapies which utilise ET less challenging.

Vibrotactile stimuli could be used to present calming and pleasant affective touch, touch which provokes an emotional response or communicates an emotion. In many ways affective vibrotactile stimuli are ideally positioned to help socially anxious individuals to feel calmer and regulate their emotions during stressful social scenarios. They (1) can be experienced without requiring conversational faculties like voice, sight or hearing, (2) can be delivered discretely to avoid the stigma of using assistive devices [200] and (3) vibrotactile stimuli can, and already do, augment a variety of different devices including smartphones and watches. Prior work has successfully used biofeedback vibrotactile cues to reduce anxiety by modulate anxiety symptoms by presenting external stimulation emulating a relaxed heartbeat [11,43] or breathing rate [145]. Affective haptics could also be used to intervene in the vicious cycle of social anxiety by facilitating emotion regulation [102] in two other ways [146]. First, calming and evocative haptic stimuli could be used to divert attention from the physiological anxiety symptoms and negative thought patterns caused by social anxiety toward a pleasant, non-threatening external sensation [89]. Second, they could be used to effect cognitive change by cuing up positive thoughts or thought of past experiences. The use of vibrotactile stimuli in this way is, however, limited by their narrow affective range [85, 230, 240]. Vibrotactile cues which elicit more meaningful, pleasant and calming emotional responses could enable new interventions for social anxiety exposure and add a new affective component to existing interfaces that vibration can augment.

A method that has been successfully utilised by other auditory and haptic stimuli to elicit more varied and meaningful emotional responses is to evoke past user experiences along with the associated emotional responses to those experiences. This thesis terms this effect as 'emotional resonance' and its potential can be seen in prior work. Patients undergoing surgical procedures have had their perceived pain lowered and felt calmer when allowed to select and listen to audio recordings of natural phenomena they find calming, such as running water or birdsong [8, 215]. Multimodal interfaces have used visual metaphor, sound cues and haptics to evoke real-world experiences, such as social robots like *Paro the Seal* which evoke interactions with real animals [94, 198]. Arrays of vibrotactile actuators have also been used to overcome their individual narrow affective range and produce emergent patterns that are evocative of natural phenomena or social touch [47, 199]. It is unclear, however, if emotional resonance can be leveraged to expand the affective range of vibrotactile cues generated from a single actuator. There are several advantages to using single vibrotactile actuators, they are small, can augment a variety of different objects, be presented across many body locations and are also integrated into a host of devices such as smartphones, watches and game controllers. If single-actuator vibrations can be emotionally resonant, their flexibility and discretion could allow for the presentation of calming and meaningful emotional experiences into new scenarios, such as social settings.

Investigating a vibrotactile intervention for social anxiety also draws attention to the lack of prior research on this topic. It is unknown what the specific requirements and preferences of socially anxious people are for such an intervention. Which real-world phenomena and pre-existing modes of affective touch would they want emotionally resonant vibrations to evoke? What is the breadth of user preferences and how do their emotional associations with these vibrations vary? What factors does the use of such an intervention in socially anxious settings depend on? In addition the method of delivery for these stimuli must be considered; what device or object should these stimuli augment? Any object augmented with calming haptic stimuli for use in social exposure could be said to take the role of a 'comfort object', objects with which the user has a emotional association that provides comfort and facilitates emotional regulation [6, 33, 72]. There is no clear understanding for what shape or texture these objects should have, how user preferences for these aspects vary, and how the augmentation of comfort objects with emotionally resonant vibrotactile stimuli impacts the emergent affective experience. Working with socially anxious users would allow these questions to be answered, resulting in the design of a calming vibrotactile intervention directly informed by users' lived experiences. This intervention could then evaluated by measuring its impact on the anxious responses of socially anxious users during social exposure, along with qualitative feedback.

This thesis investigated the use of single-actuator affective vibrotactile cues as a calming intervention for socially anxious users during social exposure, with accessibility of exposure therapy as initial driving motivation (see 6.6.8). Due to the narrow affective range of single-actuator vibrations, emotionally resonant vibrations were explored as a method of eliciting more pleasant, calming and meaningful emotional responses than previously used vibrotactile waveforms. User preferences and suggestions were used to inform the exploration of a set of emotionally resonant vibrotactile stimuli and how other factors could impact their effectiveness and applicability, such social setting, temperature, or host-object shape and texture. Participatory design with socially anxious participants informed the design of calming intervention, personalisable emotionally resonant vibrotactile comfort objects tailored to each individual's preferences, and this intervention was then evaluated in a social exposure scenario using physiological and psychological anxiety measures, as well as subjective qualitative feedback. The findings of this research would serve to widen the affective possibilities of vibrotactile interfaces, inform the design of haptic comfort objects and interventions for socially anxious users and explore the potential benefits of using emotionally resonant vibrotactile comfort objects for socially anxious people. The research path of this work is visualised in Figure 1.1.

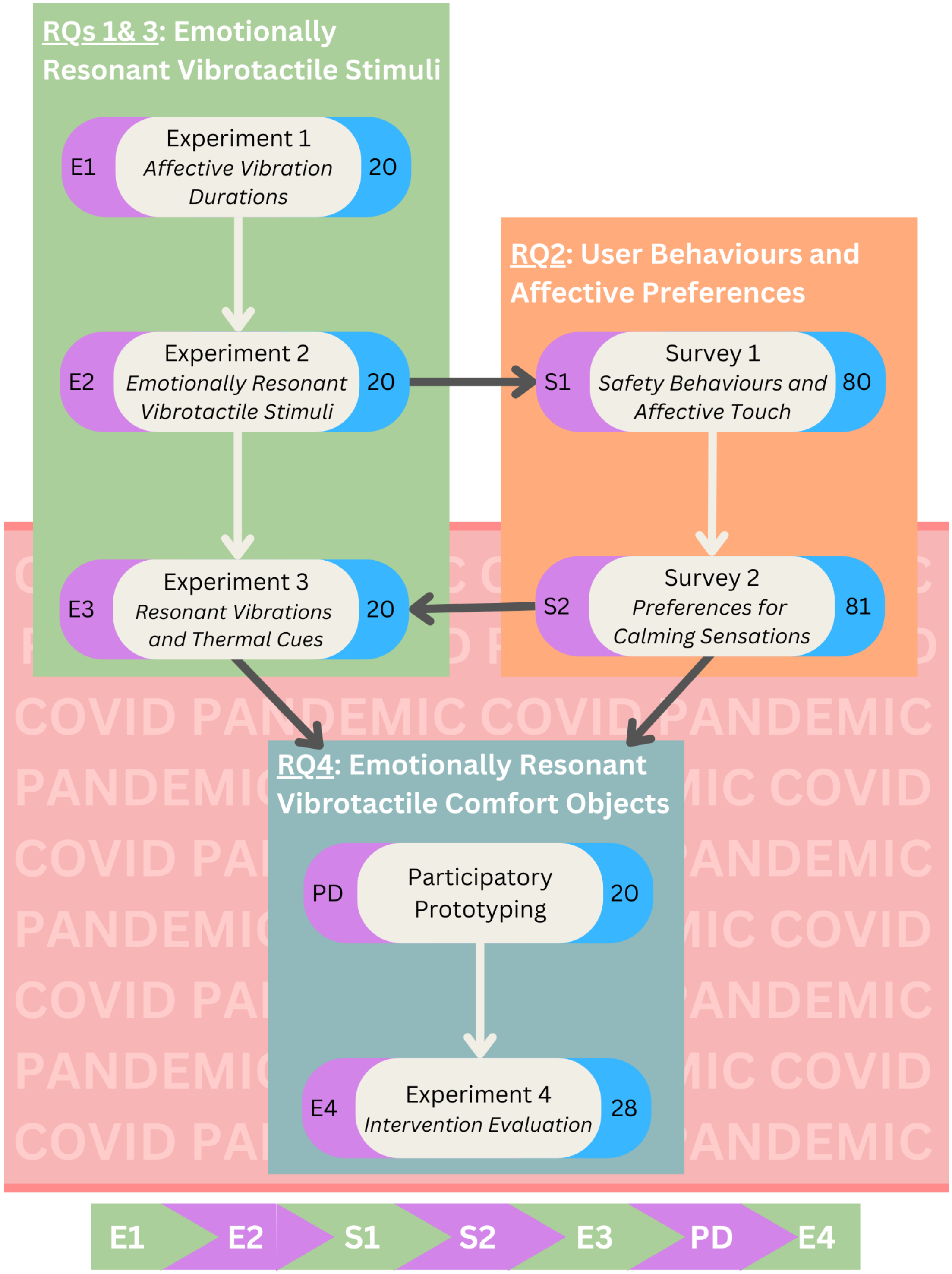


Figure 1.1: Diagram of the research path followed in this thesis. Studies are grouped by chapter and research question. Each study is shown with an acronym used in the bottom timeline (shown over purple) and the number of participants (shown over blue). White arrows show the path of discovery within chapters, while grey arrows show instances where a study from one chapter lead to a study in another. The chronological order in which the studies were executed is shown at the bottom of the figure. The period of the research which was conducted during the COVID 19 pandemic is also shown. More details about the limitations this imposed can be found in Section 6.6.11.

1.2 Thesis Statement

This thesis investigates using affective haptics as a calming intervention for socially anxious users to reduce the difficulty and discomfort of social exposure. This research developed a novel category of vibrotactile stimuli which evoke real-world sensations to elicit calming emotional responses, termed emotionally resonant vibrations, and used them to augment comfort objects informed by participatory prototyping alongside socially anxious users. Although no consistent significant effect on physiological anxiety symptoms was found, results showed that interacting with personalised emotionally resonant vibrotactile comfort objects can reduce the subjective anxiety of some socially anxious people, and that these users viewed these haptic objects as both calming and helpful in managing their anxiety symptoms.

1.3 Research Questions

This thesis answers to the following research questions:

- **Research Question 1:**
  Can single-actuator vibrotactile stimuli be emotionally resonant of real-world sensations?
- **Research Question 2:**
  Can thermal cues be used to enhance the emotional resonance and affective range of vibrotactile stimuli?
- **Research Question 3:**
  Which calming real-world experiences would users prefer emotionally resonant vibrotactile stimuli to evoke and what factors impact their use in social settings?
- **Research Question 4:**
  Can emotionally resonant vibrotactile stimuli calm socially anxious users during social exposure?

1.4 Philosophical Research Approach

The research undertaken in this thesis followed a mixed-methods approach and adopted different methodologies. This ranged from within-groups quantitative evaluation of affective stimuli during laboratory studies, to open-coding qualitative analysis of surveys or interviews, participatory prototyping, and ending with a between-groups laboratory study using a mixture of physiological measures, psychological measures and qualitative feedback. When considering it in the context philosophical research approaches, such as Positivism or Constructivism, this could be categorised as a Pragmatist's approach [53, 83], as Easterbook *et al.* write: "pragmatists use any available methods, and strongly prefer mixed methods research, where several methods are used to shed light on the issue under study" [53]. Taking a "pragmatic approach to meaning" [83] is focused on providing solutions to problems by seeking to "optimize the fit between humans and machines" [83], and accepts that the truth it aims to find is "approximate and incomplete" [53]. This was an appropriate stance for two reasons. First, when dealing with matters of emotion, for which there does not exist any singular ground truth, but merely models and interpretations, pragmatism accepts an approximate understanding and seeks to find the best way to utilise it. Second, by taking a pragmatic approach, this work sought to understand how calming emotional sensations could be evoked from hardware that is simple, easy to use, and easy to personalise. While other more complex haptic interfaces can elicit a variety of emotional responses [199, 238], exploring if simple, more practical interfaces can also achieve this result contributes toward a solution more readily available and usable by different people and in different situations (socially anxious settings, in the case).

1.5 Thesis Outline

In Chapter 2, *Literature Review*, research areas that inform this work are reviewed, both on a foundational level and investigating more modern and specific work. The key areas are: social anxiety and its traditional interventions, research exploring HCI interventions, basic haptic perception, the scope of affective haptic implementations and its utility in anxious settings.

Chapter 3, *Emotionally Resonant Vibrotactile Stimuli*, addresses Research Questions 1 and 2 describing three studies that investigated and developed a novel category of vibrotactile stimuli designed to expand the modality's affective range using emotional resonance. Experiment 1 addressed the affective impact of increasing the duration of vibrotactile cues. Experiment 2 implemented emotionally resonant stimuli and tested their affective range. Experiment 3 then investigated how adding a thermotactile component impacted the affective range and emotional resonance of the stimuli.

Chapter 4, *User Behaviours and Affective Preferences*, builds upon prior social anxiety literature and answers Research Question 3 by eliciting experiences and emotion regulation strategies from socially anxious participants and affective touch preferences suggested and selected by respondents. Two surveys were conducted: Survey 1 investigated emotion regulation and affective touch preferences; Survey 2 explored preferences for calming sensations in different social scenarios.

Then in Chapter 5, *Participatory Design and Evaluation of Vibrotactile Comfort Objects*, socially anxious users were brought into the process. Participatory Prototyping featured an unstructured interview with socially anxious participants about how they experienced and coped with anxiety, before asking them to build a calming vibrotactile comfort object. Preferences from this task informed the design of higher fidelity vibrotactile prototypes in Experiment 4, which tested the calming effect of comfort objects, customised to the preferences of participants, during a social task, addressing Research Question 4.

Chapter 6, *Conclusions*, discusses the findings and limitations of the research in relation to the Research Questions and summarises its contributions, giving recommendations for future research and the conclusions drawn from this thesis.

Chapter 2

Literature Review

2.1 Introduction

This chapter presents a review of research in areas related to the research questions addressed in the thesis. Section 2.2 details research on Social Anxiety and Social Anxiety Disorder, required to inform any attempt to design an intervention for users with these conditions. It starts with foundational research of Social Anxiety, followed by emotion regulation and how it can be used positively or negatively to manage the condition. Then established interventions will be discussed and finally prior attempts in HCI research to produce new or augmented intervention techniques. Section 2.3 presents a grounding in contemporary affective haptics research and its foundations of human haptic perception and affective computing theory. Affective applications of different haptic technologies are presented, from simple cues to complex social robots, then research informing the theory behind emotional resonance is discussed.

2.2 Social Anxiety

2.2.1 Social Anxiety Background and Cognitive Modelling

Social Anxiety is the fear of negative evaluation during social performance [176, 207]. At the point that social anxiety causes "clinically significant distress or impairment in social, occupational, or other important areas of functioning" [3] and the symptoms cannot be attributed to another condition, it is classified as Social Anxiety Disorder (SAD) [3, 151]. SAD is a common mental health condition with a lifetime prevalence of 12% [109]. Social anxiety can also be co-morbid with (occur simultaneously with) conditions such as Traumatic Brain Injury [48] and ADHD [190], or any condition which can have a noticeable impact on social functioning. Social anxiety is a stigmatised condition [207] and can have significant adverse effects on those who live with it. Co-morbidity with depression is common [125, 176], as is social isolation [133, 176]. Additionally, social anxiety can inhibit functioning during social situations [46, 133, 176], reinforcing fears of negative evaluation.

Social anxiety research has undergone significant progression over the last four decades, reflected in changes to subsequent editions of the American Psychiatric Association's highly influential Diagnostic and Statistical Manual of Mental Disorders (DSM) [1–3]. First recognised in the DSM-III as Social Phobia, specific research on social anxiety, its diagnosis and treatment was sparse [125]. Often it was under diagnosed and not differentiated from better understood conditions like Panic Disorder [125] and several studies grouped multiple anxiety disorders together when assessing them [15, 177]. In the 90s Social Phobia began being reclassified as Social Anxiety Disorder as specific understanding of the condition grew. This led to it being identified as the most common anxiety disorder [207] with an estimated prevalence among the general population over a 12-month period ranging from 6.8% [109] to 7.1% [207]. The potential impact of the condition on quality of life includes finding lowered potential job and leisure selection based on lower-social contact, the prevalence of self-isolating at home and the risks of self-medication via substance abuse [3]. Additionally, a wider range of co-morbid conditions was recognised to include Depression, Autism Spectrum conditions, ADHD and others (see Figure 2.2) [48, 190, 207].

Some researchers began exploring thought patterns and cognitive factors in social anxiety, identifying that socially anxious individuals overestimate their negative social performance [142] and the likelihood of negative evaluation from others [130] and observing that self-focus on anxiety symptoms and performance drove further anxiety [142, 177]. Rapee and Heimberg's influential Cognitive-Behavioural Model of Anxiety in Social Phobia unified these findings [176] and is foundational in modelling how social anxiety works (see Figure 2.1. It describes how increased self-focus on anxiety symptoms and perceived negative evaluation work to create a negative feedback loop that worsens one's self image and increases the perceived likelihood of receiving further negative evaluation (see Figure 2.1). Socially anxious individuals develop a long-term overly negative mental image of themselves in social situations which affects how they perceive their future social interactions [46, 176]. Later work on social cognition has found that social interaction is influenced by one's belief of what a conversation partner thinks and wants, rather than their actual behaviour [68], and that closely observing a conversation partner for signs of disapproval increases the chance of perceiving feedback as negative [151], further reinforcing why deeply held expectations of negative evaluation can further worsen social performance. The Cognitive-Behavioural Model serves to highlight points at which an intervention could impede this loop; (1) by reducing the gap between perceived negative evaluation and actual evaluation, or (2) by diverting attentional resources assigned away from self-focus on one's mental representation of outward appearance and interoception of anxiety symptoms [146].

The societal transition to widespread internet and social media use presents raises new questions for how users with social anxiety interact with computers and with other people online,

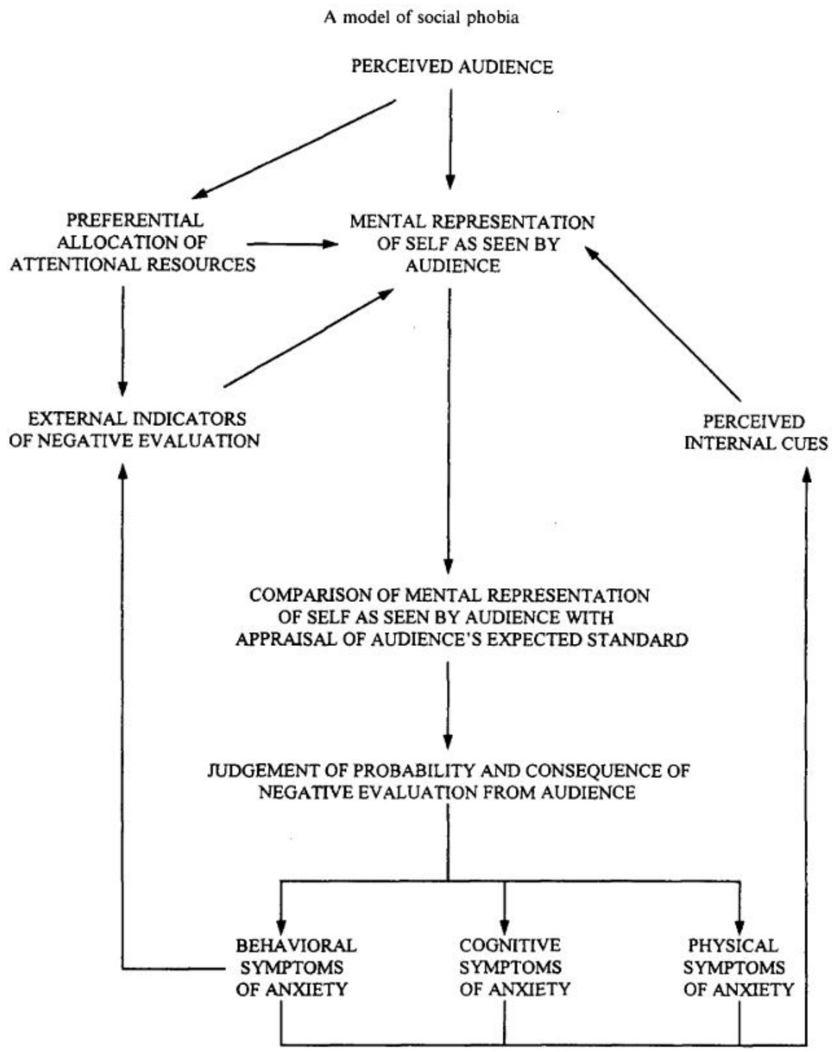


Figure 2.1: Rapee *et al.*'s cognitive-behavioural model of social anxiety, foundational to contemporary understanding of the condition. Demonstrates how anxiety is created and maintained in social situations via a negative feedback loop of perceived negative evaluation and anxiety symptoms (extracted from [176]).

and what impact this can have. Early research found that, by utilising computer-mediated communication (CMC), individuals with SAD can be socially re-enabled, particularly when forming communities with users that share their experiences [58, 82]. Socially anxious users appreciate CMC due to the lack of pressure to correctly observe social cues, the ability to plan their communication due to its asynchronous natures, and the ability to better tailor how they present themselves [172, 225]. While this allows for increased social confidence within these online spaces, this confidence does not necessarily translate to face-to-face (FTF) interactions [32, 58, 82] and can lead instead to increased social avoidance and maladaptive views about their suitability for future FTF communication [32, 123]. Whether the internet is used actively or passively also has an impact: those using primarily instant messaging may experience reduced depressive symptoms but those who spend significant time surfing and observing conversations experience

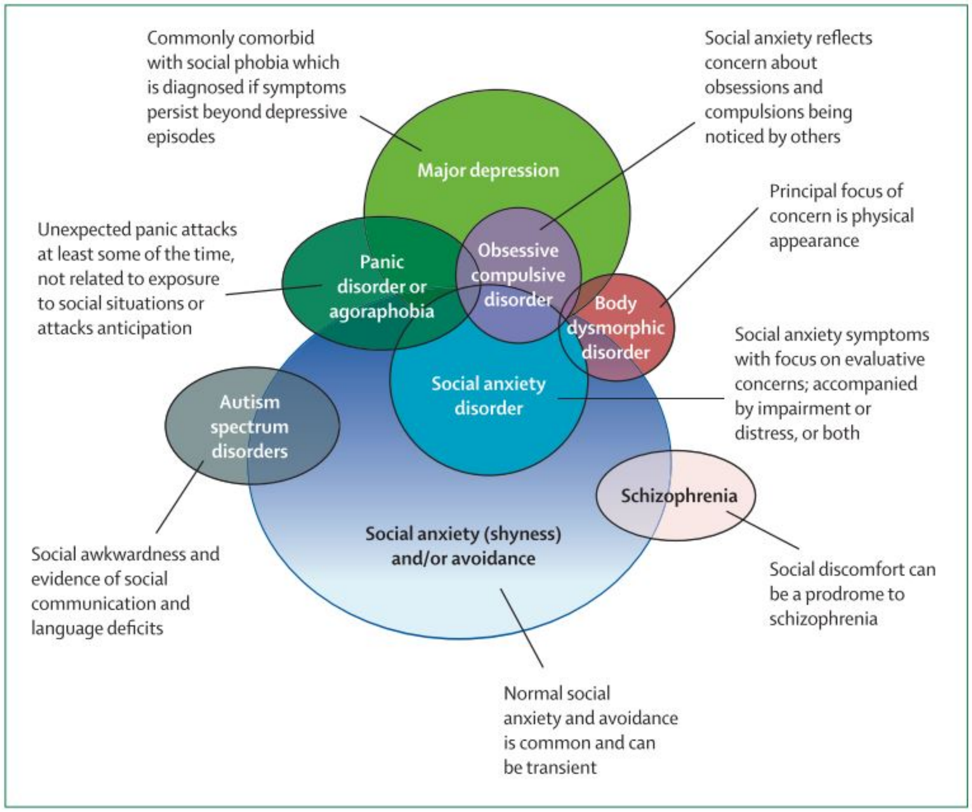


Figure 2.2: Stein *et al.*'s diagram displaying and summarising prominent mental health conditions commonly co-morbid with social anxiety or Social Anxiety Disorder. Illustrates a wide range of conditions for which social anxiety is relevant and a concern, far beyond only SAD (extracted from [207]).

worsening symptoms [194, 196]. Those with SAD can tend toward problematic internet use as they fill time with non-social passive interaction, leading to worsening loneliness [32, 137, 225]. Heavy use of online gaming also correlates with SAD symptoms [128, 172], an activity that often requires minimal social disclosure and direct interaction. Finally, the internet offers a direct and highly accessible way to engage socially anxious users with therapeutic interventions while circumventing the difficulties of traversing a FTF social space to start receiving help [58, 123] (see 2.2.3).

In summary, social anxiety research has greatly advanced since SAD was first recognised as an area of importance. The base characteristics: a fear of negative social evaluation, and its adverse effects on quality of life, are well understood. There are influential and developing theories regarding the cognitive mechanisms that drive this behaviour, such as attention to threats, self-focus on anxiety symptoms and development of a long-term mental representation of one as socially inept. The following section reviews the field of Emotion Regulation: the mechanisms used to manage emotion and their potential pitfalls, which in turn informs how social anxiety interventions conceptually work and is key to understand when introducing and justifying a new intervention in this thesis. With that context, foundational and current pharmacotherapy and psychotherapy for social anxiety can then be discussed, followed by how HCI research has sought to tackle the condition. With a full understanding of the condition, pre-existing HCI and medical interventions and the different affect regulation strategies they employ, the novel intervention explored by this thesis will be discussed.

2.2.2 Emotion Regulation and Safety Behaviours

Emotion can impact one's judgement of social interactions and perception of self-state. Emotional state is associated with subjective interoceptive awareness of body signals like heartbeat timing [45], a key indicator also associated with perception of one's own social anxiety [16, 41, 214]. Additionally, emotions have a cognitive influence on perception and decision making, excess emotion has been linked to irrational judgements while an impaired ability to feel emotion normally can negatively impact decision making [170]. Positive emotion can positively bias perception of an individual's current experience. Given this, it is valuable for socially anxious individuals to attempt emotion regulation to avoid their judgement of social evaluation or their perception of the self being negatively biased, further fueling future social anxiety (see Figure 2.1).

Emotion regulation "refers to how we try to influence which emotions we have, when we have them, and how we experience and express these emotions" [77]. For social anxiety, this represents how individuals might try to mitigate negative emotions during a social situation [102]. As this thesis aims to design an intervention which reduces anxious emotional response during exposure therapy, understanding the mechanisms of emotional regulation and which approaches can be helpful or harmful is key. Compared to social anxiety research, interest in emotion regulation is relatively recent, strongly influenced by Gross' 1998 review of emerging research [75]. They describe two broad kinds of emotion regulation strategy: *Antecedent-focused* strategies used before emotional response has fully begun and *Response-focused* strategies used once the emotional response is ongoing. Within this classification there are five points during a given emotional response event where different emotion regulation strategies may be used [76, 77] (see Figure 2.3). These are, using the example emotional response event of a socially anxious person in a job interview, as follows:

Situation Selection e.g. choosing to withdraw from the interview ahead of time.

Situation Modification e.g. attempting to steer conversation away from stressful topics.

Attentional Deployment e.g. focusing one's vision on around the room rather than on the facial expressions of the interviewers.

Cognitive Change e.g. downplaying the importance or severity of the interview in one's mind.

Response Modulation e.g. trying to hide anxiety symptoms from the interviewers.

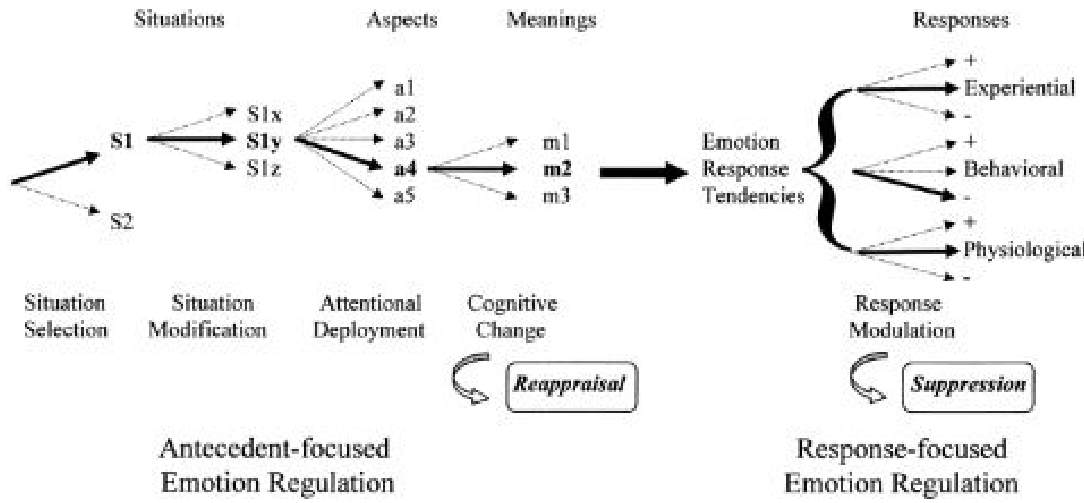


Figure 2.3: Process model of emotional regulation demonstrating the five points in emotion generative process where emotion regulation processes can take place. Those marked antecedent take place while emotional generation is incomplete, those marked response take place during or after emotional response (from [77]).

Emotion regulation strategies can have different consequences, constructive or damaging. For example, Situation Selection may give a socially anxious person short term relief but may lead to future social isolation, whereas Cognitive Change is a key mechanism of Cognitive Behavioural Therapy (CBT), a front-line psychotherapy for social anxiety [160]. Response Modulation has also been shown to incur a higher cognitive load than Cognitive Change, worsening social performance and performance on memory tests [76].

An essential topic when discussing how emotion regulation is used by socially anxious people is Safety Behaviours. A Safety Behaviour is defined as an “overt or covert avoidance of feared outcomes that is carried out within a specific situation” [187] and by using those actions one may feel ’saved’ from the perceived threat [187]. For those with social anxiety, this specifically means actions taken to reduce perceived negative impact of social situations. These actions can vary greatly and encompass different emotion regulation strategies. An overt action might be avoidance of a feared future social situation or use of computer-mediated communication instead, i.e. Situation Selection [172, 173]. More covert actions might be limiting eye-contact and interaction by focusing on one’s phone [23], i.e. Attentional Redeployment. The potential impact of safety behaviours on long-term rehabilitation is much debated. Morgan *et al.* hypothesised that ’being saved (i.e. using a safety behaviour to avoid an anxious event) strengthens the person’s belief that their safety behaviour prevented likely danger but makes disconfirmation of threat-related cognitions unlikely’ [148]. Indeed, meta-reviews have found that safety behaviours can result in worse outcomes for social anxiety psychotherapy that aims to promote cognitive change [23,148,183]. There have, however, been calls for the reconsideration of safety behaviours. Rachman *et al.* highlights that, while safety behaviours are associated with worse therapy outcomes, adherence to therapies that utilise exposure can be challenging for those with anxiety disorders [65,173,203]. "Judicious" use of safety behaviours can be used to offset these adherence challenges, then tapered off later in the process as they are less needed.

In summary, social anxiety safety behaviours are actions taken to reduce the impact of a perceived dangerous event and can, if left unchallenged, reinforce disproportionate fear of social situations and obstruct rehabilitation. When designing an emotion regulation intervention for exposure therapy, therefore, it is important that it will not act as a damaging safety behaviour, allowing the user to deploy their attention away from the exposure. This thesis aims instead to develop an Antecedent-Focused haptic intervention that would use Attention Deployment differently, providing an external, calming stimuli for users to focus on rather than their internal anxiety symptoms, like elevated heart rate and breathing rate [11, 43, 233]. Additionally, providing stimuli which cue up calming or pleasant thoughts may help the user to reduce rumination on perceived external negative evaluation [176], enabling Cognitive Change during social exposure. Both outcomes could reduce the difficulty of facing your fears during the social exposure central to psychotherapies like CBT. As both internal physiological symptoms and external social feedback are the key contributors to the self perpetuation of social anxiety, as per the cognitive-behavioural model [176], this haptic intervention has the potential to reduce social anxiety during social exposure.

2.2.3 Social Anxiety Therapies and Interventions

There has been an expanding exploration of possible interventions to curb the symptoms of social anxiety and the impact it has on those who live with it. Understanding how these methods work and what each aims to achieve allows a better understanding of how new or augmented interventions can be developed. These interventions can be divided into three categories: Psychotherapy, Pharmatherapy and alternative interventions. In the following section each will be discussed in turn.

Psychotherapy, also known as talking therapy, involves individuals with a mental health concern working with a mental health professional to change behaviours, perception or thought patterns that are negatively effecting their quality of life, based on established psychological principles [66]. The most prevalent psychotherapy for social anxiety, both historically and currently, is Cognitive Behavioural Therapy (CBT) [60, 125, 207]. CBT uses a combination of exposure events (either in-person or simulated), conducted both within and outside of therapy sessions, cognitive restructuring (CR) designed to correct problematic perception and behaviour in those events, social skills training (SST), and relaxation techniques [60, 207]. It utilises the strategy that cognition changes affect regulation as the therapist aims to help socially anxious patients challenge their pessimistic perception of negative social evaluation, then put those new thought patterns into practice during social exposure. This exposure component of the controlled repetition of facing one's fears, also called Exposure Therapy (ET), is itself a first line intervention with proven efficacy [23, 60, 140] and was discussed earlier in regards to how safety behaviours may lessen its impact (see Section 2.2.2). The focus of this thesis was the development of a haptic intervention which could be utilised during social exposure to reduce anxiety, which could make adherence to Exposure Therapy easier, making the proposed intervention highly relevant to these core social anxiety treatments.

The efficacy of CBT in reducing social anxiety symptoms has been demonstrated [60, 160] and improvements emerge after six to twelve weeks of sessions [191]. In a meta-analysis of 108 trials, Fedoroff and Taylor found that all components of CBT had significant positive effects on both self-reported symptoms and observer ratings for social performance when compared to a waiting list condition. More specifically CBT had a greater impact on observer ratings and tended to leave a lasting reduction in symptoms in follow-ups, a finding echoed in studies since [191, 207]. CBT can be conducted as individual therapy or in a group, although there is evidence that one-to-one is more effective [153]. Given its status as a therapy option for social anxiety, and other conditions [160], there have been attempts utilise new technologies to maximise access to it via internet implementations [34, 88] or virtual reality exposure [136, 149] (see Section 2.2.4 for detailed discussion).

The affective haptic social exposure intervention developed in this thesis is highly relevant to CBT because it utilises Exposure Therapy as a core component. This is also true of other less prevalent but established psychotherapies, such as ACT and DBT. Acceptance and Commitment Therapy (ACT) is an iteration of traditional CBT which prioritises the context of problematic events in helping patients to defuse and move past traumatic events, enabling future exposure and acceptance [86]. ACT can be as effective as CBT depending on the patient [9, 100, 158]. Dialectical Behaviour Therapy (DBT) was developed to tackle patients who were difficult to collaborate with and would actively combat the idea that they could make positive changes [127, 211]. It takes special attention to validate the feelings and views of the patient, often with irreverent, matter-of-fact debate, and helps move patients toward acceptance of negative events. As acceptance is achieved the therapist then helps the patient achieve new skills and behavioural changes. It has shown potential in treating anxiety disorders and improving emotion regulation and may be especially useful for individuals who are sceptical of the value of talking therapy [157]. CBT, ACT and DBT all include an exposure component as a core part of the process, allowing patients to test their changed behaviours and challenge their assumptions. Augmenting therapy with a calming affective haptic intervention could further improve treatment efficacy by improving accessibility and adherence to social exposure. Psychotherapy is, however, only one part of traditional treatment for social anxiety alongside Pharmatherapy, with which it is often used in tandem.

Pharmatherapy refers to using medicine to treat mental or physical health disorders. During the period of increased research interest in Social Anxiety Disorder in the 1980s some medicines were already in use to treat it and other anxiety disorders. Primarily these were anti-depressants like beta blockers and monoamine oxidase inhibitors (MAOIs), but detailed understanding of how effective they were for social anxiety had not been achieved. [125]. Contemporary pharmatherapy for social anxiety includes selective serotonin inhibitors (SSRIs) and benzodiazepines (BDZs) and MAOIs. SSRIs are the most prevalent of the three, having less limiting side effects and restrictions for use [201, 228], while effectively tackling social anxiety symptoms after four to six weeks of use [207, 228]. BDZs ad MAOIs have a higher-potency and take less time to take effect but are not as suitable for less-intense cases and can cause long term health risks and side effects [60,201,207,228]. There is no clear generalised performance effect from combining pharmotherapy and psychotherapy; the decision to employ either or both should depend on an individual's circumstances [207].

Aside from traditional psychotherapy and pharmatherapy there are other avenues to explore when supporting and rehabilitating social anxiety. Animal-assisted therapy (AAT) has shown a proven ability to reduce anxiety. In a 1998 study Barker and Dawson found that 30 minute sessions with a therapy dog and the dog's owner had a significant effect on anxiety reduction for patients with psychotic disorders and was twice as effective as therapeutic recreations [13]. Later work found that animal interaction increased neurochemicals associated with attention-seeking and lower blood pressure, providing a physiological basis for anxiety and stress reduction [163]. Following this a meta review of 49 studies found AAT had significant positive effects on several areas including emotional well-being [159]. Despite this some issues remain for use as a social anxiety intervention. While having a pet present may make some situations more pleasant their presence cannot be guaranteed and, when present, they may provide an excuse for a socially anxious individual to focus on interacting with them, rather than other people there, acting as a maladaptive safety behaviour. This provides another use case for the affective haptic intervention proposed in this thesis; a haptic stimuli which successfully evoked responses related to affective animal touch could provide the calming benefits of AAT in a wider range of social contexts and without the practical constraints of animal care.

The role of social and emotional touch on anxiety reduction has also been explored. Soothing hand-massaging alongside verbalisation has been shown to reduce anxiety in dementia patients [112], and more generally touch can be calming, soothing and communicate intimacy and approval [92], reducing the likelihood of perceiving negative evaluation. The warmth of human touch can promote feelings of closeness and pleasantness [73,226] and physical stroking on non-glaborous (hairy) skin produces a pleasant emotional response [129, 139, 152], providing a positive distraction from anxiety symptoms, a research direction current in active exploration [78]. Like AAT, however, emotional touch may not always be available or appropriate in certain social situations, making it problematic as a robust social anxiety intervention. Here, again, is an opportunity for the emotionally resonant haptic intervention developed in this thesis to make an impact, allowing anxious users to access calming and familiar emotional touch discretely in any social scenario. Prior to this thesis, however, was a body of HCI research which also explored how to leverage 21st century technology in support of helping those living with social anxiety.

2.2.4 HCI Interventions for Social Anxiety

HCI researchers and designers have explored if technology could enable new interventions and therapy variants for social anxiety. This section will give an overview of the different ways these explorations have been successful and how they informed the path of discovery of this thesis.

Calming Haptic Touch

Calming touch could help reduce the impact of social anxiety symptoms. There is a growing body of HCI work exploring affective haptics (see Section 2.3.2) and some have targeted anxiety reduction as an application. Simulating affective human touch is one approach. Edelson *et al.* reported early findings that a machine exerting lateral pressure designed to 'hug' autistic participants reduced skin conductance, a physiological anxiety measure [54] and since then other 'hugging' setups have been trialled [154] and may have therapeutic potential [25]. A review of haptic psychotherapy research directions found potential in haptic arrays that simulate stroking or soft human touch [25], of which functional prototypes have been made [25, 47, 96]. Social robots can also be a platform for soothing affective haptic interactions designed to reduce anxiety. Hall *et al.* used a zoomorphic robot, The Haptic Creature, to explore the effect of emotional touch on anxiety with a pet-like robot, with promising physiological and qualitative findings [78]. Social Robots 'Huggable' and 'Emobie' were designed to reduce anxiety in pediatric patients [10, 103] and, while their efficacy was not well established, 'Huggable' did increase social interaction. 'Paro the Seal' similarly prompted a similar increase in elderly care home residents [223]. The ability for these haptic arrays and social robots with fundamental touch interaction to promote socialising and reduce anxiety symptoms showed the promise of affective haptics to be calming in social contexts, prompting the research questions addressed in this thesis: can simpler single-actuator stimuli also elicit calming emotional responses and do they also have applicability in social settings.

Emotion Regulation and Biofeedback

Affective haptics can also be used to augment emotion regulation strategies and improve their effectiveness. Miri *et al.* describes how haptic stimuli can facilitate emotional regulation in three ways: through distraction from internal anxiety symptoms, triggering beneficial thought patterns when experiencing a haptic stimuli or using biofeedback to improve response modulation [146]. Bucolo *et al.* demonstrated that tangible interaction with an interface, even without an active haptic component, can serve to divert attention from pain and anxiety in pediatric patients [31]. Others have utilised biofeedback as an emotion regulation tool. Biofeedback training helps users to modify their physiological responses with the aid of live feedback of their own physiological state, e.g. using a visual indicator of one's breathing rate and a comparison to a slower rate, encouraging the user to match both rates and thus reduce their anxiety levels [141]. Early investigations of affective haptics hypothesised using it to present biofeedback to aid in relaxation training [134] and later research directly explored this.

Several studies have explored the use of haptic stimuli that mimic a heartbeat. Azevedo *et al.* developed a watch-like device that delivered a tactile simulation of a slow, calm heartbeat to the wearer's wrist and found it reduced self-reported stress and arousal during a speech anticipation task [11]. These findings were echoed by both Xu *et al.* and Costa *et al.* using a similar wearable implementation with a slow tactile heartbeat [43, 233] and by Choi *et al.*'s 'ambienBeat' which presented a tactile heartbeat-like pulse, below the threshold of tactile sensitivity to avoid distraction, to the wrist and found it effective in guiding the user to a calmer heart-rate [38].

Haptic interfaces have also been designed to assist in regulating breathing-rate and, subsequently, emotions. Parades *et al.* developed a car seat augmented with an array of vibrotactile motors which allowed users to synchronise their breathing to a sweeping pattern of vibration travelling up and down their back, without interrupting their vision or control of the vehicle [166]. 'BrightBeat' used a combination of biofeedback modalities: visual, audible and thermotactile, purposefully tuned to run slightly slower than the users' current breathing rate to help them slow their breathing [70]. The 'PIV' used C-2 tactors placed on the chest, stomach or back to provide a discrete pacer used to regulate breathing speed. Their results highlighted the importance of personalisation in biofeedback, as Miri *et al.* found using a personalisation routine to suit individual differences in heart rate and breathing rate resulted in improved efficacy [145].

Biofeedback has also been explored using visual and auditory cues [36, 204]. Smith *et al.* reported a significant reduction in anxiety prevalence for participants using a biofeedback and mindfulness phone app over a four week period [204]. Hamon *et al.* explored displaying heart-rate biofeedback using an illuminated environmental object participants could focus on directly or experience in an ambient way [80], finding that direct attention on the object resulted in higher relaxation. Finally, Virtual reality has also been used with promising effect to present breathing and heart rate biofeedback and can do so inside of a calming, immersive environments [181,222] (see Figuire 2.4).

Biofeedback delivered in a virtual environment or via a phone interface does not, however, allow access to its benefits during social exposure without disrupting conversation. Haptic biofeedback could be delivered discretely during social exposure, however, prior work has not thus far measured its efficacy in this context. This thesis directly addressed this question, testing how effectively affective haptic cues helped socially anxious users to regulate their emotions during face-to-face social exposure.

Figure 2.4: Left: An example of a calming immersive environment implemented in virtual reality. Right: Shows an example of biofeedback as a UI indicator and the environment itself react to the users heart rate (extracted from [181]).

Virtual Reality Exposure Therapy

In the field of anxiety interventions, virtual reality has been used to simulate and facilitate Exposure Therapy. Virtual Reality Exposure Therapy (VRET) emerged in the last decade, having numerous advantages over traditional methods: the exposure experienced can be tailored and controlled by a therapist [149, 179, 217] and allows easy access to immersive exposure events in the therapist's office [51, 179]. In multiple meta-analyses VRET has shown similar efficacy to traditional Exposure Therapy, tackling a large variety of fears and anxiety disorders [136, 149, 217]. Researchers have also used VRET specifically to tackle social anxiety utilising simulated public speaking scenarios and found it produced a significant reduction in social anxiety when compared to normal Exposure Therapy both immediately after treatment and in a 12-month follow up [7, 185]. The biggest disadvantage to VRET is accessibility: virtual reality headset ownership and therapists who supports its use are not widespread, and establishments that can support this burgeoning therapy may be expensive to use. Given this there is still a need for alternative interventions, like that proposed in this thesis, which improve the experience of standard face-to-face exposure therapy experienced by most users undergoing therapy for social anxiety.

Internet-Delivered Psychotherapy

The internet is a more traditional digital platform for computer-mediated psychotherapy. Delivering psychotherapy via computer or smartphone can improve accessibility by making more people aware of the how to get help [34, 88], as research suggests only 25% seek treatment [34], and online therapy allows access while forgoing the need for socially anxious users to enter physical social spaces to begin face-to-face sessions [88]. These implementations either replace the role of the therapist or allow a therapist to communicate with the user via computer-mediated-communication. Internet-delivered CBT (ICBT) has shown efficacy in treating social anxiety and SAD when hosted online [34, 88, 213] or with a smartphone application [100]. While ICBT makes CBT more visible and accessible, it doesn't reduce the inherent difficulty of facing social exposure addressed by this haptic intervention in this thesis. If said intervention was found effective, ICBT applications could both integrate CBT materials and use the host-devices haptic actuator to provide calming haptic sensations during exposure, providing a more supportive experience for users.

Lifelogging

HCI research has also worked to aid socially anxious people maintain the practice of lifelogging. Lifelogging is a CBT practise of automatically or manually tracking anxiety events so they can then be considered later and unduly negative thoughts re-evaluated [178]. Automatic life-logging can help by removing the cognitive load of remembering to record stressful events and can capture events that the user may not have thought to record, all of which can then be evaluated later on. While this thesis does not propose a lifelogging intervention, lifelogging devices are required to be discrete, portable objects which can perform their function without disrupting normal daily functioning, with some tailored to the needs of users with anxiety. Lifelogging devices informed the design of affective haptic objects in this thesis because they share many of the same requirements.

Miranda *et al.* investigated if using smart-glasses that recorded blink rate or a heart rate monitor could effectively detect anxiety events, although only heart rate offered promising results [144]. Berrocal and Wac [20] explored combining automatic collection of physiological signals with corroborations of observations from family members and friends to give a clearer picture of the mental state of participants in stressful scenarios. There is a long history of using heart-rate, heart-rate variability and skin conductance as possible indicators for social anxiety (see 2.4.2 for a full review). Rennert *et al.* took another approach: the wearable 'FaceIt' camera which captured still images of the users current situation when triggered by detection of social interaction, elevated heart rate and certain GPS locations [178]. This combination of pictures, heart rate and location can then be viewed holistically later to allow for evidence-based re-considerations. There are also advantages to using technology to better enable manual lifelogging. A smartphone prototype by Mohammedali *et al.* provided calming and instructive aid to users at the point of event recording while simplifying the process of recording an event and contacting a carer or therapist if needed [147]. Ferrario *et al.* explored an approach dubbed 'intentive computing' whereby the user actively chose when to instigate physiological data capture but through a simple, discrete button press [63]. They found this approach helped users to both remember when anxious events took place and provided a sense of control, relief and closure to those events. This research group also explored the role of form factor and personalisation in lifelogging devices, co-designing tactile wristbands alongside participants [202]. Participants highlighted the different kinds of positive and negative events they wished to log and results cited the advantages of allowing users to make assistive devices their own; ‘thus reducing abandonment and increasing benefits to users’. In general, efforts to make lifelogging easier and more effective are a valuable way to make another key aspect of CBT and other therapies easier for patients to engage with. They do not, however, necessarily make the act of engaging in social exposure easier.

Conclusion

One can observe that the majority of HCI interventions for anxiety, including social anxiety, are grounded in established psychotherapy and designed to make these processes more accessible or effective, although there is space for more experimental approaches, such as the ‘Icebreaker’ T-shirt designed to help socially anxious users initiate face-to-face conversation and feel greater social closeness with others [111]. But when developing new computerised interventions researchers also need to consider the stigma and social misconceptions that those seen visibly using assistive devices are subject to [200]. Those using such devices have reported that others perceive their ability to function as inexorably tied to their use of that devices and they are less able to avoid stigma as the device advertises their disorder or disability [200]. This gives affective haptics a usability edge over other categories of intervention, they can be used discretely within social exposure events without disrupting conversation or provoking stigma. Affective haptics is, however, an emerging field and lacks research specifically developing and testing it as an intervention for users with social anxiety. This thesis fills this gap, applying affective haptics as a calming intervention specifically in relation to the needs and requirements of socially anxious users undergoing exposure therapy.

Intervention	Acronym	Description	Notes	Sources
Psychotherapy				
Exposure Therapy	ET	Planned exposure to feared scenario to reduce fear and avoidance.	Core component of many other interventions.	[23, 60, 140]
Cognitive Behavioural Therapy	CBT	Guided therapy to help cognitive restructuring and positive reconsideration following ET.	Highly prevalent and flexible with many variants and adaptations.	[60, 125, 207]
Acceptance & Commitment Therapy	ACT	CBT variant highlighting acceptance of negative events.	Prioritises the unique contexts of traumatic events.	[9, 86, 158]
Dialectical Behaviour Therapy	DBT	Uses irreverent, matter-of-fact and accepting language to engage participant in debate.	Targeted for combative patients.	[127, 157, 211]
Animal-Assisted Therapy	AAT	Animal interaction/touch reduces stress.	Limitations based on social context.	[13, 159, 163]
Pharmatherapy				
Monoamine Oxidase Inhibitors	MAOIs	Powerful antidepressant, previously front-line drug for social phobia and panic disorders.	Causes dietary restrictions, strong side effects.	[201, 207, 228]
Benzodiazepines	BDZs	Powerful antidepressant, can reduce symptoms in as little as one day.	Can cause long-term health risks.	[60, 201, 228]
Selective Serotonin Inhibitors	SSRIs	Front-line antidepressant with 4-6 week lead in.	Low risk of long-term side effects.	[201, 207, 228]
HCI Research				
Internet-Delivered CBT	ICBT	Conducting CBT using web apps and CMC.	Increases the accessibility of CBT.	[34, 88, 213]
Social Robots		Affective touch with social robots can reduce anxiety and promote social interaction.	Non-discrete intervention, risks assistive device stigma in public settings.	[78, 103, 223]
Virtual Reality Exposure Therapy	VRET	Therapists utilising VR to create and control immersive exposure events.	Presently inaccessible for vast majority of patients due to hardware cost and recency.	[136, 149, 217]
Lifelogging		Aiding in logging anxiety events for reflection.	Focused on improving CBT progress.	[144, 178, 202]
Emotion Regulation Devices		Devices which divert attention resources from internal anxiety symptoms.	Can utilise biofeedback to help users reduce physiological anxiety symptoms.	[11, 31, 43]
Biofeedback		Gives user real-time feedback on physiological signals to help them calm their breathing etc.	Can also display an artificially calmer signals for user to sync up with.	[36, 181, 204]
Computer-Mediated Touch		Tactors simulating stroking found calming.	Applicability for social anxiety unclear.	[25, 47, 96]
Thesis Intervention				
Emotionally Resonant Haptics		Reminiscent of sensations users have positive associations with to produce calming haptics.	Discrete and flexible applications due to simple vibrotactile implementation.	[132, 199]

Table 2.1: Overview of interventions and HCI research aimed at support anxiety disorders with direct or potential applicability to social anxiety.

2.2.5 Social Anxiety Summary

Social anxiety is the fear of negative social evaluation and is a prevalent mental health issue which adversely effects quality of life. Cognitive modelling of social anxiety (see Figure 2.1) theorises that social anxiety is characterised by an erroneously negative view of the social self, which heightens one's awareness of internal anxiety symptoms and predisposes one to perceive more negative social evaluation than is actually received, causing a feedback loop which perpetuates further social anxiety. Those with social anxiety use affect regulation strategies to attempt to manage their emotional responses before or during social situations. Certain strategies, such as Response Modulation and Safety Behaviours, can prove maladaptive and serve to reaffirm the validity of an individuals social fear. Other strategies like Cognitive Change, however, can help the individual reconsider their negative perceptions and is a core component of front-line social anxiety psychotherapy. The most prominent psychotherapy used to treat social anxiety is CBT, which utilise exposure events to challenge the patient's misconceptions with the guidance of a trained therapist. Due to the prominence and efficacy of CBT, HCI interventions have primarily sought to augment existing CBT practises and make them more widely accessible. Rarely, however, have these efforts focused on the needs of socially anxious users specifically and a primary challenge that impedes their progress, the difficulty of facing one's fears and adhering to exposure therapy.

This highlights the need for HCI research which works specifically alongside socially anxious users to understand their needs during social exposure. Simultaneously, haptics are ideally positioned as an intervention during social interaction which can be experienced discretely and non-disruptively. This prompted Research Questions 3 and 4 and formed the primary motivation for this thesis, which seeks to make exposure therapy easier to adhere to for socially anxious users, utilising discrete and calming affective haptics. As a note, much of the research directly investigating the mechanisms of social anxiety focused on SAD, social anxiety symptoms also arise from many other conditions. This thesis investigates providing an intervention for social anxiety not limited by origin condition and supplements prior knowledge with first hand empirical observations on the requirements and experiences of socially anxious users (see Section 5.2).

2.3 Affective Haptics and Computing

Having discussed the potential for affective haptics to discretely provide a calming intervention during social anxiety exposure therapy, without disrupting conversation or inviting stigma, prior affective haptics research is now surveyed to inform how to deliver calming haptic cues. First, the foundational field of Affective Computing will be briefly discussed and haptic perception will be reviewed to understand the design space and limitations of haptic interfaces. With that established, different affective haptic modalities and their individual strengths, limitations and prior applications will be reviewed in turn and the chosen modality for this project's exposure therapy application justified.

2.3.1 Affective Computing

While this section of the review is focused on understanding the scope and applications of Affective Haptics research, it is prudent to review the foundational areas of Affective Computing and Haptic Perception upon which it is based. Affective Computing was defined in Picard's foundational essay as "computing that relates to, arises from, or influences emotions" [170]. At this early stage a few possible implications of affective computing were theorised: (1) computers that can recognise emotions could better understand and serve the needs of users in the given moment, (2) computers could use expressed emotion to more naturally communicate with users, (3) computers could better simulate human intelligence and decision-making of which emotions are a neurological component [170]. A wearable emotion monitor had already been prototyped by Picard *et al.* using physiological signals like heart rate and skin conductance [169]. Expressing emotion during communication with users has been explored using AI-controlled computer service agents, finding that agents demonstrating care for the user were significantly preferred to those with neutral presentation [22], although many participants cited that, while they enjoyed feeling caring and acceptance, the artificial nature of caring affect was hard to ignore. Affective computing also presents unique opportunities to provide empathetic support for individuals who face challenges in traditional social environments. Kaliouby *et al.* highlighted emotional interpretation technology could help autistic users better understand social cues [55].

Assessing affective devices and software requires a way to measure and categorise the user's emotional response. A prominent model for measuring affect is Russell's Circumplex Model of Affect [184]. This model maps valence (pleasantness to unpleasantness) and arousal (alertness to sleepiness) to a two-dimensional plot with neutral intersection between both scales (see Figure 2.5). Thus the Circumplex Model allows designers and researchers to assess emotional response to affective computer interfaces using just these two self-reported measures. This model is widely used in the assessment of affective haptic interfaces [21, 73, 85, 232, 240].

Assessing emotion in this manner must, however, be done with full knowledge of the simplifications and omissions present in treating emotion as objective information [24]. Emotion is a complex phenomenon and measuring it via two linear factors cannot express a complete picture of how somebody is feeling, gives no insight into why they feel that way, and how many external confounding factors are at play. Boehner outlines an alternative approach to emotion interpretation: 'emotion-as-interaction', attempting to view, and help users view, emotion within the social, cultural and, when measured, experimental context it emerges from [24]. According to Boehner, it is not incorrect to try and make objective measures of emotion, but judgements made on these measures must account for limited view they offer. When designing an affective computing intervention for socially anxious users, taking a holistic and qualitative approach to

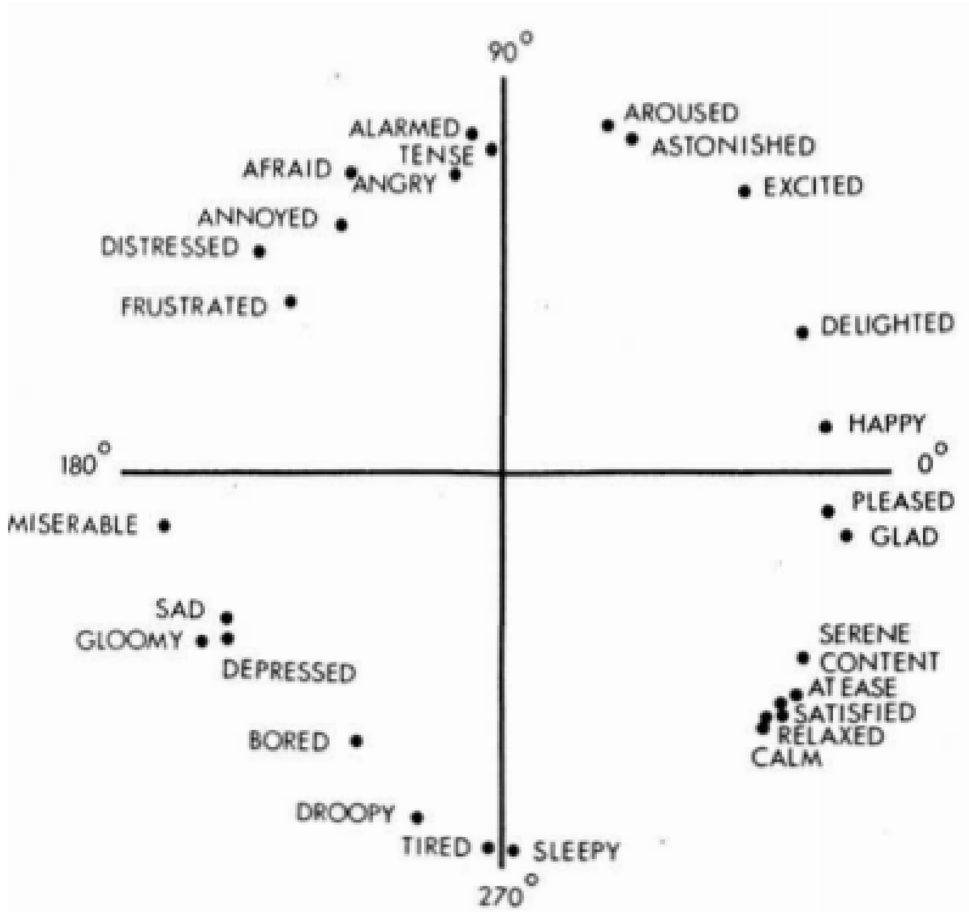


Figure 2.5: Russell's Circumplex Model of Emotion [184]. The y-axis represents arousal or alertness, while the x-axis represents valence or pleasantness. Russell mapped 28 different affect terms around this circular model (extracted from [184]).

observing emotional responses provides valuable insight into their specific experiences and subsequent requirements. This directly informed analysis conducted in this thesis will combined quantitative emotional response data with qualitative interviews providing context.

2.3.2 Human Haptic Perception

Haptics refers to 'both cutaneous sensations gained from the skin, also referred to as tactile feedback, and the kinesthetic sense, which involves internal signals sent from the muscles and tendons about the position and movement of a limb' [220]. Understanding the features and limitations of the physiological mechanisms which detect haptic feedback is vital to understanding the bounds of the design space for haptic interfaces. This review will focus on the the cutaneous system due to its relevance to affective touch and affective haptics. The cutaneous system refers to the sensory processing of the skin [138]. Embedded in the skin are mechanoreceptors, skin receptors which are 'specialised to transduce mechanical forces impinging the skin into nerve impulses' [138] and thermoreceptors, myelinated fibers which detect cold and unmyelinated

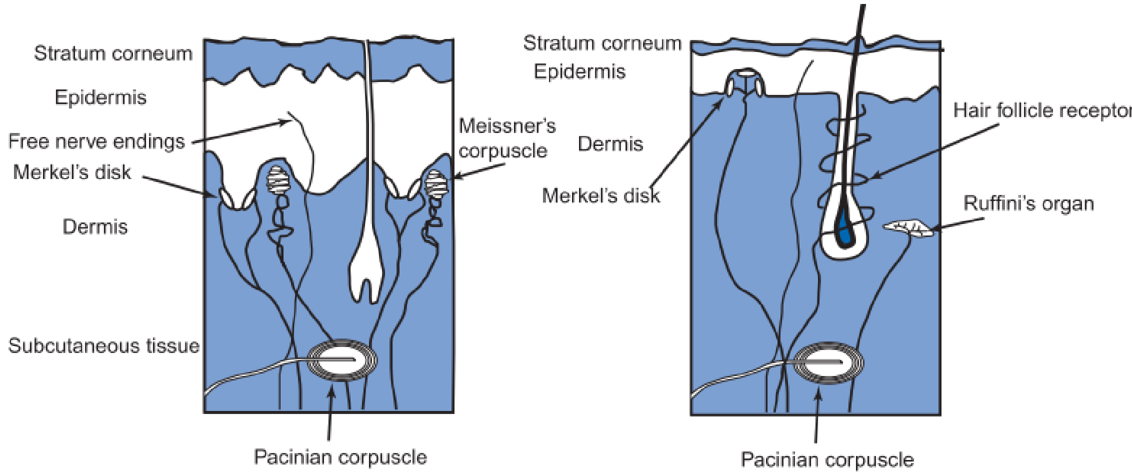


Figure 2.6: Cross-section diagram of the mechanoreceptors found in the skin. Shown left is glabrous (hairless) skin and shown right is hairy skin. Each has a different make-up of mechanoreceptors (extracted from [61]).

nerve endings which detect warmth [61, 122].

In practical terms, these mechanoreceptors process discriminative touch, encompassing the perception of (1) material properties like texture, (2) object properties like shape, size and numerosity and (3) tactile sensations like pressure and vibration [67, 105, 139]. While mechanoreceptors are found within all skin, there are differences in the combination of and prevalence of different receptors and subsequent haptic perception depending on if the skin is glabrous (hairless) or non-glabrous (hairy) [122] (see Figure 2.6). Both contain a Pacinian corpuscle, a fast-adapting free nerve ending within a capsule that enables it to perceive vibration, while glabrous skin also contains Meissner's corpuscles, fast-adapting capsules that respond to lower frequency vibration. Collectively these capsules are referred to as FA (fast adapting) channels. Merkel's disks found in both skin variants are slow-adapting receptors which respond to steady pressure and Ruffini's corpuscles are slow-adapting found in hairy skin which detect pressure and the push or pull of skin, together referred to as SA (slow adapting) channels. Adaptation here refers to an increase in perception threshold after a prolonged exposure to haptic stimulus, resulting in deadening of sensation [221]. Free nerve fibres are found in both skin variants, detecting tactile sensations, but in hairy skin they also entwine hairs and detect lateral movement of the hair [61].

C Tactile (CT) afferents, a class of nerve fibres, are only found in hairy skin [122, 138] and activate from the movement of hairs and extremely soft skin deformation (0.22 grams of pressure) [152]. Whereas other mechanoreceptors mediate discriminative touch, CT afferents mediate emotional touch, making them of particular note for affective haptic applications [139]. Sensations like stroking or brushing, particularly within a velocity range of 1-10cm/s, have been found to elicit a strong pleasant emotional response [129, 139, 152]. CT afferents adapt to a stimulus after approximately four seconds and stop triggering [152] and varying the location or avoiding long presentation is advised. Although CT afferents mediate emotional touch, that is not to say that there is no emotional response associated with discriminative touch. Bianchi *et al.* posited that “an affective counterpart always exists in stimuli delivered through haptic devices, although designed to convey discriminative information exclusively” and proposed a methodology of eliciting arousal and valence scores from participants per haptic stimuli [21] and plotting the results on The Circumplex Model [184], an approach used commonly in the field. Indeed, affective haptic research has explored many implementations to both leverage emotional touch stemming from CT afferents, and measure emotional response to discriminative touch sensations via valence and arousal, in pursuit of designing affective interfaces (for full discussion see Section 2.3.3 and 2.3.4).

Specific haptic sensations used in this thesis - the perception of vibration, shape, texture and temperature - have specific haptic perception requirements and considerations. The following sections will note this requirements and considerations and how they inform the use of these modalities in this work.

Vibration

Vibrotactile perception thresholds are dependent on vibration frequency; the overall range of vibrations the skin is sensitive to is 20-500Hz [131, 221], but different frequency ranges are detected by different mechanoreceptors. The Pacinian channel (P channel) allows perception of frequencies above 40-50Hz, while other non-Pacinian channels (NP channels) are most sensitive below 40Hz and produce a ’fluttering’ sensation [104, 131, 150]. The P channel governs vibrotactile perception in glabrous skin [39], whereas hairy skin contains a lower number of P channel receptors and thus lacks sensitivity to a wider range frequencies [39]. Additionally, the P channel is subject to temporal summation, an effect whereby sensitivity to vibration becomes higher as sensation duration increases, until adaptation is reached [39, 138, 221]. Areas with glaborous skin like the palm, the fingertip and the underside of the wrist present the most promising locations for varied vibrotactile stimuli presentation, as the prominence of both P and NP channel receptors allows for the widest frequency range of sensitive vibration perception. The just noticeable differences (JND) between different vibrotactile stimuli varied by intensity and frequency is approximately 10%-30% for intensity and 15%-30% for frequency [39]. Further considerations must be made when presenting multiple stimuli in different locations or at different times, as this can cause confounded spatial or temporal perception [39, 122, 221] or even produce emergent new perceived sensations like simulated motion [221].

Texture

The perception of texture is a holistic haptic experience utilising tactile, thermal and kinesthetic channels [119] and encompasses a wealth of possible sensations, from a hand gliding across a smooth surface to scraping and deforming along a rough one. The most significant early work on texture perception is Katz's 1925 book *The world of touch* [107]. Katz focused on lateral motion across surfaces resulting in perceived vibration in the skin, arguing this was key to the perception of roughness, smoothness, hardness or softness [107]. Observations included increased force leading to greater perceived roughness and at higher lateral speed discrimination between paper of different roughnesses became less perceivable [107, 119].

More contemporary research echoed these findings by Katz but also found other factors texture perception depends on [119]. Roughness was shown to scale strongly with the width of grooves in otherwise smooth surfaces [120] and deformation of the skin was shown to be crucial in roughness perception, rather than vibration as Katz's suggested [107, 119]. Temperature also plays a role, as skin temperature is lowered below baseline surfaces surfaces are perceived as smoother [74]. Texture perception can also suffer from adaptation, although this effect is reduced for rougher surfaces [105].

Temperature

Temperature is perceived by the cutaneous system within a range of 5°-45°C [122]. This occurs when a temperature level higher or lower than the body's internal state is detected (the temperature of the skin of the hand rests between 25°- 36°C) [122, 138, 167]. Warmth is perceived by unmyelinated free nerve endings and cold by myelinated free nerve endings. Both have a phasic component (rapid initial response) and tonic component (slower, long term response) [61]. This means temperature change can feel more intense upon initial exposure then it does during long-term immersion [61]. Perceived temperature also can also depends on material. A surface that feels cold when touching it extracts heat from the skin and this speed of conduction varies depending on the heat conductivity of the material (e.g. metals are highly conductive), the shape of the object (heat travels faster through a short, thick object) and the texture (rough textures with lower surface area have worse heat conduction) [105].

There are spacial considerations to consider when using thermal feedback as some parts of the body such as the hands, and particularly the area of the palm directly next to the thumb, are very sensitive while others, like the face, are not [208, 209]. Additionally thermal stimuli can suffer from *spatial summation*: when presented in close proximity can result in stronger perceived sensation and confound the ability to distinguish specific location [234]. Ambient temperature can impact perception. Research has identified 15°-20°C as a ideal range for detection [79] and have been shown to worsen above 25°C [229]. Strigo *et al.* tested temperature and pain perception at three ambient temperature levels: 15°C, 25°C and 35°C. They found that when cold stimuli were experienced at an ambient cold temperature, thermal pain and sensation were reduced [210]. Additionally participants found hot and cold stimuli more unpleasant when presented in corresponding hot and cold rooms. Finally, there is also an inherent emotional component to temperature, as warmth bears an association with interpersonal warmth [227] and warm stimuli have been found more pleasant than cooler stimuli [73, 230].

Shape

The form factor of an object can also impact its haptic perception. Shape can dictate the ways in which individuals interact with an object, known as an Exploratory Procedures (EP) (see Figure 2.7) [121]. For example, a cylindrical shape may prompt the user to wrap their fingers around it, while a flat surface provokes sliding one's hand across it, and a contour invites touch that follows along the curve. These different interactions may use different areas of skin and thus be sensitive to different sensations such as vibration or temperature [122] Research carried out in this thesis had participants designing haptic comfort objects with free reign over the shape, size and texture (see Section 5.2) and thus it prudent to keep in mind that varying these factors may result in varying perception of vibrotactile stimuli between people. Visual processing and material properties are also thought to have some bearing on haptic perception of shapes and discrimination between objects by touch may be poorer without visual feedback [105, 122].

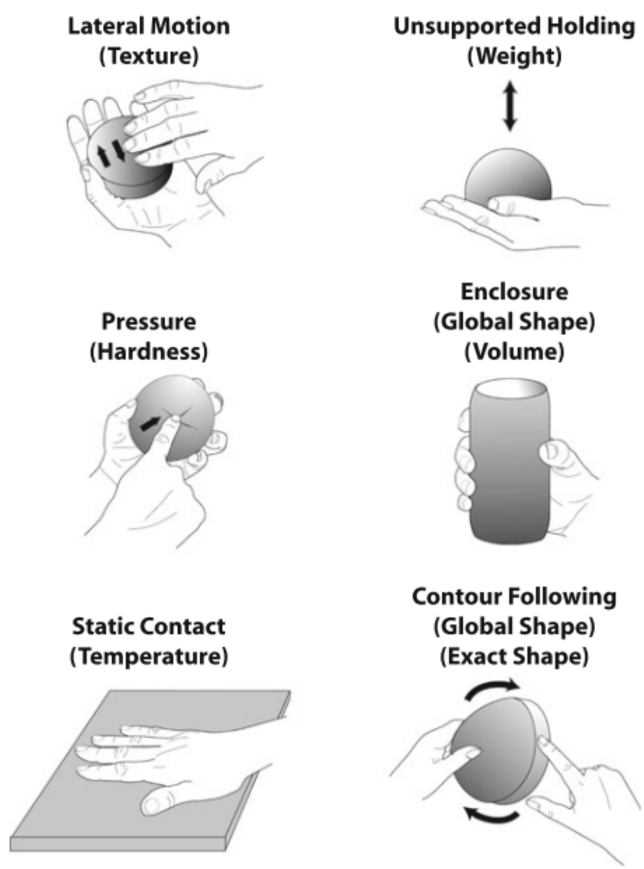


Figure 2.7: Diagram demonstrating six different kinds of exploratory touch, what they assess and they can be impacted by shape (extracted from [121]).

Considerations Made for Haptic Perception

Reviewing the capabilities and limitations of human haptic perception allows better understanding of affective haptic research and for a series of considerations to have been made throughout the research which constituted this thesis. The cutaneous system uses a variety of different skin receptors to enable the perception of haptic sensations including texture, pressure, vibrations, temperature and lateral movement. Hairy skin also contains CT afferents, free nerve endings which trigger a strong positive emotional response to skin stroking, particularly at speeds between 1-10cm/s. Triggering CT afferents in social scenarios is currently impractical, however, as apparatus used in prior work is large and non-portable when compared to vibrotactile actuators (see Section 2.3.3).

Emotional touch is also possible on glaborous skin. Of particular relevance to this thesis is the haptic perception of vibration, texture, temperature and shape. Vibration sensitivity varies by location. While glaborous skin is most sensitive to frequencies above 40Hz, it is also still sensitive below 40Hz, meaning stimuli presented in this thesis were restricted more by apparatus rather than haptic perception limitations. Vibration sensitivity can lower over time due to adaptation, a concern addressed by Experiment 1. The perceived roughness of textures depends on the pressure and speed of traversal. As discussed later in Section 2.3.5, the roughness of a texture can influence its pleasantness, but specific textures may have specific emotional associations [98]. Thus, this thesis opted to offer participants a range of texture options to suit their personal preference.

Temperature is accurately perceived by the cutaneous system within a 5°C-45°C range. Perception suffers from adaptation and some body locations like the hands are most sensitive. When presenting thermal cues in Experiment 3, presentation would be made to the hands and within this Celsius range, while maintaining a consistent ambient temperature. Finally, the shape of an interactable object can dictate how people hold and interact with it, and thus which skin locations make contact with haptic surfaces, impacting perception. When conveying vibration through objects of different shapes, as in Chapter 5, the object should make good contact with the sensitive glabrous skin to ensure proper perception.

Understanding haptic perception informs the design of haptic interfaces seen in prior affective haptics research and the limitations that governed those designs, as well as the haptic interfaces used in this thesis. The next section will discuss prior research on different affective haptics modalities, their potential applications and how this informed the research path of this thesis.

2.3.3 Affective Vibrotactile Stimuli

Vibrotactile stimuli are highly variable, ranging from simple abstract vibrations varied by waveform parameters [29, 240] to interfaces utilising multiple actuators to produce emergent, meaningful patterns [96, 199]. Additionally vibrotactile displays can be presented to different body locations such as directly to the hand for maximum sensitivity [85, 230, 240], or to the wrist or arm via wearables [11, 43]. This section will discuss the diverse field of affective vibrotactile research, beginning with simple, fundamental stimuli before progressing to more complex interfaces.

Emotional Responses to Vibrotactile Parameters

Research investigating the perception and information conveyance of simple vibrotactile stimuli, such as Brewster and Brown's 2004 Tactons [29], is less than two decades old and the exploration of emotional responses to such stimuli is even more contemporary, with foundational papers still emerging [85]. Specifically, the impact on emotional response by variance of vibrotactile waveform parameters: frequency, amplitude, duty ratio and duration (see Figure 2.8), was studied. Research findings on the affective properties of each of these parameters will now be discussed.

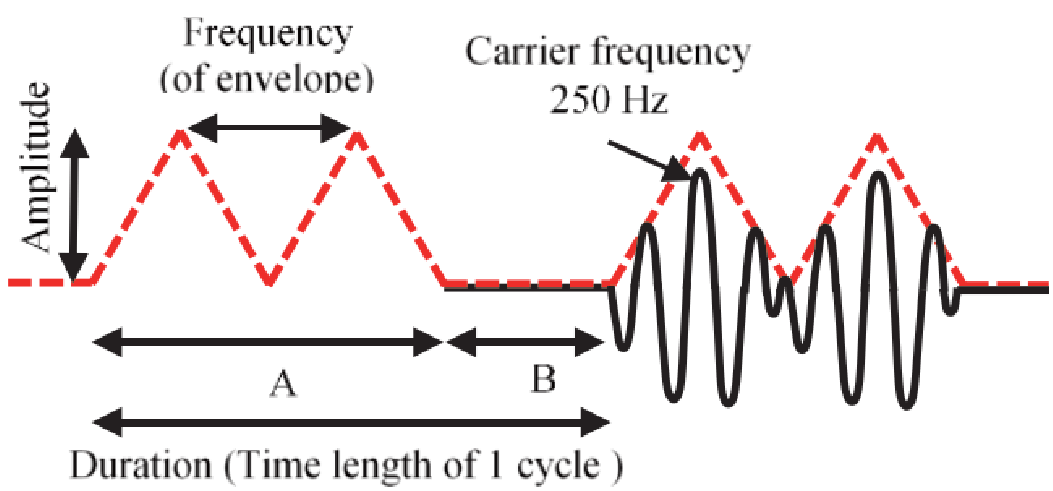


Figure 2.8: Diagram of a saw-tooth vibrotactile waveform. Amplitude indicates the height of the wave's envelope peaks. Envelope frequency indicates the interval between envelope peaks. Carrier frequency indicates the interval between individual pulses that make up the larger saw-tooth pattern of the wave. Duty-Ratio indicates how much of the cycle contains active stimulation (A) and how much does not (B). Duration indicates the total length of the stimuli. (extracted from [85]).

Amplitude

The amplitude of a vibrotactile stimulus refers to the peak of the wave envelope (see Figure 2.8) and, in practical terms, governs the intensity of the vibration: a higher amplitude results in a stronger vibration. The majority of prior work has demonstrated that amplitude has clear effects on emotional response, finding that participants gave a higher arousal rating to stimuli with a higher amplitude [5, 85, 230, 240]. Discussing valence, Yoo *et al.* found amplitude had a negative effect on valence at lower envelope frequencies levels of 60Hz and 100Hz, but no effect on at and above 150Hz [240], while other researchers found that amplitude reduced valence (or the equivalent comfort and preference used by Hasegawa *et al.*) at all levels of frequency [5, 85, 230]. It is worth noting some of the earliest work in the field by Seifi *et al.* did not find a significant effect of amplitude, instead finding that frequency and rhythm dominated affective response [193]. The majority of findings, however, suggest at an inverse relationship between arousal and valence in relation to vibration intensity.

Frequency

Frequency of a vibration refers to the rate of vibration waveform and governs how fast the user perceives it to be. Two variants of frequency are relevant to vibrotactile signals: carrier frequency and envelope frequency, both of which have been studied to ascertain their affective properties. Carrier frequency refers to the rate of the vibration itself, whereas envelope frequency refers to the speed at which the envelope of the vibration repeats, the envelope being the outer limits of the waveform which may form an emergent pattern (see Figure 2.8). Seifi and Maclean observed that carrier frequency had a significant positive impact on arousal [193]; 175Hz stimuli rated higher than 75Hz. Yoo *et al.* and Wilson *et al.* echoed this, finding that frequency had a positive effect on arousal [230, 240], although Akshita *et al.* found that when viewing low-arousal images lower frequencies resulted in higher arousal [5]. Findings are divided on carrier frequency effects on valence, with Wilson *et al.* and Yoo *et al.* finding higher frequency resulted in lower or higher valence respectively, despite similar stimuli [230, 240], while others found no significant effect [5, 193]. The effects of varying envelope frequency are less explored and inconclusive. It has been shown to have both a positive [85] and negative main effect on valence [85, 240] and while Hasegawa *et al.* found a strong negative impact on arousal [85], Yoo *et al.* found no conclusive effect [240].

Duty Ratio and Duration

Duty ratio refers to the percentage of each stimulus made up of active vibrotactile presentation [85] (e.g. a duty ratio of 100% represents vibration for the entire stimulus duration, whereas a duty ratio of 50% presents vibration for half of the stimulus duration). Hasegawa *et al.* investigated this parameter, finding that larger and more continuous duty ratios elicited lower arousal and more comfort, but the effects were not conclusive as some participants found that larger ratios - resulting in longer stimuli - resulting in more intensity due to temporal accumulation, reducing comfort [85]. Another variable to consider when presenting a stimuli below 100% duty ratio is how the vibration and downtime are interspersed. Hasegawa *et al.* simply placed all the vibration at the start of the stimuli, as seen in Figure 2.8. Seifi *et al.*, however, investigated the impact of different rhythms (see Figure 2.9) and found rhythm was the dominant affective parameter in their study [193]. Longer uninterrupted vibrations were perceived as more pleasant while stimuli that were shorter or featured more pauses were more arousing and less pleasant. Duty ratio also impacts duration, as smaller ratios result in shorter stimuli. Research has explored the impact of duration on affective response. Yoo *et al.* tested a range of duration levels from 50ms to 2000ms, finding that increasing duration resulted in increased arousal, but valence was independent [240]. Wilson *et al.* tested two levels, 100ms and 1000ms but found little effect [230] and Hasegawa *et al.* tested four levels between 100ms and 400ms, finding no impact on affective response.

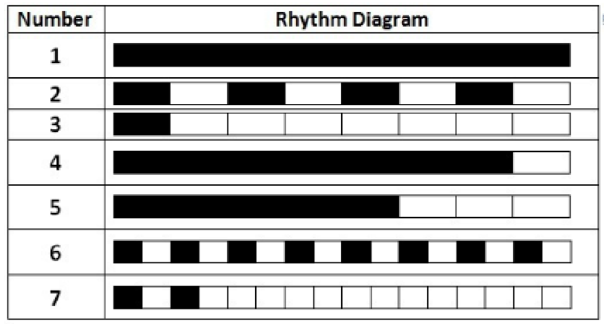


Figure 2.9: Diagram showing how Seifi *et al.* arranged non-continuous stimuli can be arranged into 6 different rhythms(extracted from [193]).

Study of the affective properties of vibrotactile parameters is still far from exhaustive and within the current body of available research, there is variance in the devices, variables and levels used. The field would benefit from both repetition studies that validate or question prior results, as well as further studies exploring new parameter levels. Relevant to this thesis, prior work makes it unclear how the affective properties of vibrations might change when stimuli duration is extended beyond the range of 100-2000ms previously tested. Researchers also noted that vibrotactile stimuli are able to access a wider range of arousal responses than valence responses and that areas of the Circumplex Model, particularly low arousal areas, have a notable narrow valence range [85, 230, 240]. Thus, while abstract vibrotactile stimuli have the potential to be flexible and convenient affective haptic tools, there is further work to do in establishing and expanding the range of emotional responses they can elicit, particularly when pleasant or relaxing cues are desirable.

Affective Vibrotactile Patterns and Applications

In isolation, single vibrotactile actuators can have a limited emotional range. Research has, however, explored ways to extend their capabilities by combining them into larger arrays of multiple actuators or presenting them alongside other stimuli. This rest of this section will discuss various ways vibration has been used in more complex interfaces to deliver further emotional experiences.

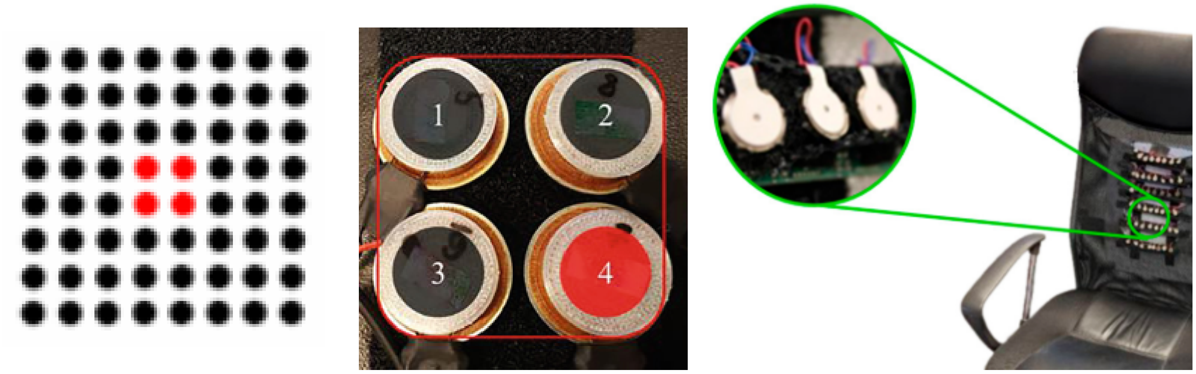


Figure 2.10: Left: An example pattern displayed on a 8x8 array of vibrotactile actuators (extracted from [17]. Center: Four larger vibrotactile tactors arranged in a grid to convey patterns (extracted from [199]. Right: A Vibrotactile array mounted to the back of a chair, allowing presentation of patterns to the back of the user (extracted from [197]).

Vibrotactile Actuator Arrays

Multiple vibrotactile actuators can be arranged in different ways to produce interfaces capable of producing larger patterns (see Figure 2.10). A simple example is a grid. Benali-Khoudja *et al.* and Israr *et al.* both experimented with flat interfaces housing a grid of small actuators [17, 99]. In both cases, participants rest their hands on the entire array in order to perceive when different columns, rows or areas vibrated. Benali-Khoudja *et al.* defined basic patterns and found that differentiation between them was possible. While they did not measure emotional response, they did find success communicating 'emotional' information, such as how the sender was feeling [17]. By contrast, Israr *et al.* described a methodology to produce meaningful stimuli by asking users to define semantic haptic patterns based on different concepts or words like 'rain' or 'engine humming' which could have emotional meaning (see Section 2.3.9) [99]. Shim *et al.*'s *palmScape* used a 2x2 Tactor array to represent meaningful sensations, such as raindrops or breathing, using different timed patterns across the 4 Tactors [199]. They made use of slight random fluctuations to better evoke natural sensations and measured emotional response, finding that these stimuli meaningfully expanded the known vibrotactile affective range, particularly into the pleasant/calm and unpleasant/arousing quadrants of the Circumplex Model [184, 199]. Shetty *et al.* demonstrated that Tactor arrays can also augment other objects: integrating a 4x4 array into the back of a chair (see Figure 2.10), presented alongside a thermotactile wristband [197]. Variance in vibrotactile pattern had a significant effect on emotional response, with longer patterns tending to cause higher valence and arousal and the most pleasant stimuli featured 'Snake' patterns during which a trail of vibrations progressed back and forth across the array.

Vibrotactile Social Touch

Vibrotactile arrays have also been used to simulate social touch by utilising sequential linear patterns to evoke stroking sensations and trigger pleasant emotional responses from CT afferents in hairy skin (see 2.3.2 for discussion of CT afferents). Prior work has utilised wearable sleeves to house these linear arrays (see Figure 2.11). Huisman *et al.* experimented with a sleeve featuring twelve vibration motors [95] before settling on four larger cylindrical motors (which allowed for better pattern recognition) and found they were able to produce patterns perceived similarly to gentle stroking with a similar emotional response [96]. Culbertson and Nunez *et al.* attempted to simulate the same sensation by utilising a sleeve with five voice coil vibration motors [47, 161]. Culbertson *et al.* used their findings to theorise the optimal placement and timing of sequential vibrations to maximise continuity and pleasantness, finding their maximum intensity value and shortest delay between actuations to be most effective [47]. Nunez *et al.* offered a comparison between the vibrotactile sleeve and an armrest interface with rotating motors which provide intermittent contact with the skin, simulating a stroking sensation [161]. While both produced a stroking sensation, the vibrotactile implementation was more pleasant. They also found only four points of contact were required to emulate stroking effectively. A simpler implementation using two C2 Tactors in a sleeve was tested by Kelling *et al.* and found overall positive participant response to the soothing touch, as well as lowered heart rate [108]. Vibrotactile stimuli can also emulate social touch without triggering CT afferents, as demonstrated by Rantala *et al.* who developed handheld interfaces which could mediate touch between participants; touching or squeezing buttons on one device resulted in vibrotactile stimuli on a paired device in the same locations [175]. Squeezing interaction best communicated negative emotions and finger touch better suited positive emotions. Generally, simulated social touch is a promising method to elicit pleasant affective using vibrotactile technology, although most implementations are limited to a specific stroking sensations and involve large wearable sleeves which limit current real-world practicality. If meaningful emotional sensations can be evoked using vibrotactile cues generated by a single-actuator, as this thesis explores, it could allow for calming and pleasant cues to augment devices and objects with a wider variety of form factors and be used covertly during social interaction.

Vibrotactile Augmented Sensations

Prior work has also experimented with using vibrotactile stimuli to augment non-haptic sensations, altering their affective properties. Early work by Standley paired simple vibrotactile stimuli alongside music or the sound of a dental drill, finding it pleasant in both contexts, although music presented on its own was still most preferred. Details of the vibrations presented are sparse [206]. More recently, Hernandez *et al.* experimented with integrating vibrotactile stimuli into a large fabric tactile sheet interface which participants could lay their hands, arms or torsos upon [91]. The stimuli varied in intensity depending on how many people interacted with

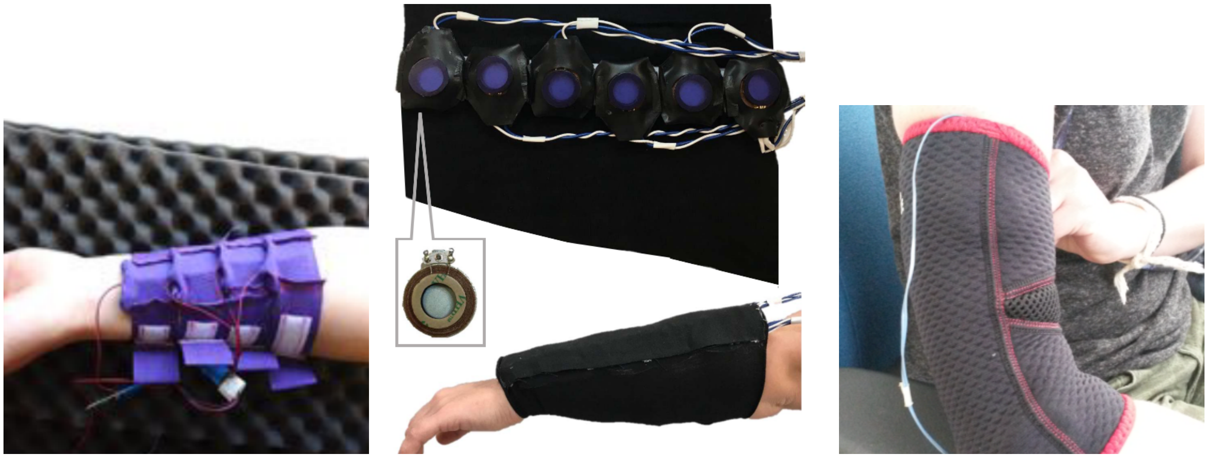


Figure 2.11: Three examples of vibrotactile sleeves featuring an array of linear actuators designed to simulate a stroking sensation in order to evoke the emotional response resulting from triggered CT afferents (extracted from [47, 96, 108]).

the interface at once, prompting playful and social interactions between participants. Karafotias *et al.* created a wearable jacket with 16 vibration motors to present four kinds of tactile cue, aimed at evoking emotional responses from the four quadrants of the Circumplex Model, during a film, with the aim of intensifying immersion and emotional response [106]. They found that this tactile intervention was always enjoyed when presented, although it failed to induce relaxing sensations, as it always increased excitement, aligning with prior research in suggesting the inability for vibration to elicit specific and varied emotional responses. Vibration has also been in social robotics to simulate certain natural behaviours like purring [94, 236], further discussed in Section 2.3.8.

Vibrotactile Emotional Regulation

Finally, vibrotactile stimuli have been used as an emotion regulation tool; specifically facilitating response modulation by simulating heartbeats or breathing to help users calm themselves [11, 38, 145, 233]. This provides another example of adding context to allow vibrotactile stimuli to impact the user's emotional state outside the narrow range of emotional response to vibrotactile parameters. The full discussion of this area can be found in Section 2.2.4.

Affective Vibrotactile Conclusion

Vibrotactile is a flexible affective haptic modality which has been applied in simple and complex interfaces. Emotional response to vibration varies with amplitude, frequency, duration and duty ratio [85, 230, 240], with arousal being the most consistently impacted and the affective range of stimuli being generally 'tall and narrow' with a wider arousal range than valence. Researchers have created more varied sensations using multiple actuators arrayed in sequence or a grid. These have been used to create complex patterns and evoke real-world sensations, resulting in a wider range of emotional responses [17, 199]. Additionally linear arrays simulating social stroking can elicit the pleasant emotional response caused by triggered CT afferents [47, 96]. Vibration can also emotionally augment other sensations, making different sound, film or images more pleasant and arousing [91, 206], although it was still unable to induce low arousal, relaxed responses, a limitation found in the majority of affective vibrotactile research. Future work aiming to expand this affective range further would be valuable, as the small size and ubiquity of vibrotactile actuators in modern devices could enable emotional experiences in a wide variety of contexts. While research has shown vibration can evoke specific pleasant real-world sensations using vibrotactile arrays, it is unclear whether the same effect can be achieved using vibrations generated by a single actuator. Additionally, no work prior to this thesis explored applying these pleasant emotionally resonant cues to the field of emotion regulation.

2.3.4 Mid-Air Ultrasonic Haptics

Haptic feedback can be delivered using an array of ultrasound transducers, normally arranged in a grid (see Figure 2.12), creating air pressure waves [231]. This is known as ultrasonic haptic feedback, or ultrahaptics. These arrays can be used to produce complex and changing patterns (similarly to vibrotactile arrays), from tracing lines and shapes [174] to simulating complex objects or even fluids [14]. While research in the space is only a handful of years old, there have been some preliminary experiments exploring its affective proprieties.

Obrist *et al.* explored augmenting the pictures from the IAPS with ultrahaptic patterns created by participants to match different images [162]. Participants found the task challenging and found the positioning and intensity of pattern elements the most useful when crafting meaningful stimuli. Once these haptic descriptions were created another group rated them alongside the source images. Participants tended to find images and their corresponding stimuli resonant with each other, appropriately fitting and their emotional response ratings altered based on the image shown. Participants were better at assessing the intended arousal, impacted strongly by intensity and frequency, of a pattern than its valence, which positively impact by frequency was somewhat influenced by the regions of the hand stimulated. In a followup paper describing data collection, Gatti *et al.* [69] used traditional valence and arousal measures, as well as skin conductivity, to record emotional responses to ten of the ultrasonic haptic stimuli which evoked real world sensations, such as rain or wind, that were validated previously by Obrist *et al.* [162]. They did not, however, conduct any analysis on said data. Azh *et al.* also explored this space, working with artists to augment their pieces with ultrahaptic feedback [12]. The artists were tasked with sketching ultrahaptic patterns to be displays directly over the artwork itself, evoking certain elements of the piece, be it theme, setting, or line/brushwork. While this resulting in highly specific and non-generalised stimuli and subsequent responses it highlights the potential design space afford by presenting complex haptic patterns mid-air. Affective ultrahaptics further demonstrate the ability for interfaces to be evocative of real-world stimuli and emotionally

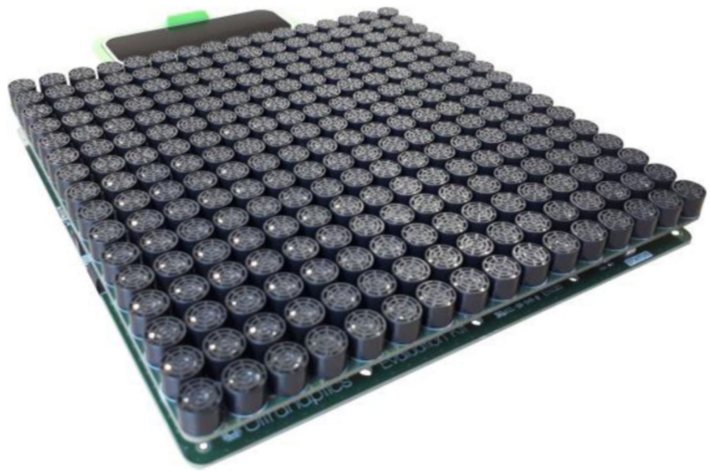


Figure 2.12: Example of a 16x16 ultrasonic haptic array. Feedback is delivered to the hand by holding it palm downward towards the array (extracted from [174]).

meaningful as a result. When compared to vibrotactile stimuli, however, applicability in social settings is limited, as they must be presented to the user's hand in a specific way and require mounting steady surface, preventing their covert use in a variety of conversational scenarios. Thus, they were not considered appropriate for use in this research.

2.3.5 Texture

Early research on human texture perception primarily focused on the how different variables, such as the number and width of grooves, affected perceived roughness [71, 107, 119]. Exploration of emotional responses to texture is more contemporary. Nagano *et al.* assessed how inviting textures were to touch by presenting participants with 24 different clay textures, varied by attributes such as grooves, perforation, and smoothness [155]. Participants found textures more inviting when they were non-glossy, dry, grooved or appeared comfortable. Iosifyan *et al.* focused instead on emotional response to perception, finding softness and roughness elicited pleasant and unpleasant responses respectively and that certain textures could be associated with emotionally charged concepts (e.g. Granite or Marble could be associated with gravestones) [98]. Etzi *et al.* performed a similar study, asked participants to rate perception of ten textures in terms of emotional response, including satin, sponge, tinfoil and sandpaper, on their hands, cheeks, and stroked along their arms [59]. Again smoother materials were more pleasant. Participants also preferred materials they had prior experience with and found perception on the arm more pleasant than hand or cheek. HCI researchers have also sought to augment interfaces with different textures to impact emotional response. *Touch Connection* was a textile vibrotactile interface which utilised smooth leatherette and soft faux fur to invite communal touch from multiple users, who then shared vibrotactile sensations [91]. Simm *et al.* utilised different textures when co-designing wearable life-loggers, allowing participants to choose between soft textile, hard plastic or rough surfaces when making their prototype their own [202]. Participants chose different textures and materials to make their wearable 'their own', with some experiencing not only soft texture as calming, but harder and sharper textures as well. It is clear there is an emotional response to texture perception, therefore it is another tool to consider exploring when seeking to enhance or to alter that affective properties of a haptic interface beyond its current limitations. This conclusion would inform the inclusion of different textures when conducting participatory prototyping in Section 5.2 when seeking to create personalised and pleasant haptic objects.

2.3.6 Affective Thermotactile Stimuli

As highlighted in Section 2.3.2, temperature has an inherent emotional component as warmth promotes social closeness [227]. Although still a burgeoning field, prior research has explored the affective properties of computer-driven thermotactile interfaces. Initial work by Salminen *et al.* using temperature levels 4°C below or above the base temperature of the hand, delivered from a Peltier thermotactile actuator, showed that warmth had a significant positive effect on arousal, although they found no effect on valence [188]. In a followup study testing three levels (2, 4 and 6 °C) of warmth and cold from body temperature, they further reported that 6°C warm shifts in temperature were unpleasant, but smaller 2-4°C shifts were pleasant, and both increased arousal [189]. Wilson *et al.* tested this range along with +/- 8°C levels, as well as two rate of change (ROC), 1°C/sec and 3°C/sec [232]. They found that generally smaller and slower changes were more pleasant and less arousing, while 6-8°C changes were arousing and unpleasant. Additionally, warm stimuli were almost universally more pleasant than equivalent cold stimuli, except for the fastest and hottest combination.

Given thermotactile stimuli have been shown as capable of producing both pleasant and alerting sensations, prior work has also explored how they might augment other experiences with affective properties. The impact of thermal stimuli on the viewing of affective images, drawn from the International Affective Picture System (IAPS) [118], has been tested, although results were inconclusive. Halvey *et al.* found warm stimuli may make emotional response to an image more pleasant, although they found whether the stimuli was delivered constantly or in pulses and how this matched the arousal and valence of the images (constant preferred for exciting images, pulsing for sad or calmer images) was most influential [79]. Akazue *et al.* found warm stimuli presented during an image could make unpleasant images even more-so, but cold stimuli reduced their impact [4]. Stimuli presented before an image tended to create anticipation, where cold stimuli created expectation of a high valence image and *vice versa*. Nakashige *et al.* experimented with using thermal stimuli to augment images with specific temperature based content (e.g. images of hot ramen or cold ice cream), participants rating images as more pleasant when presented with a resonant thermal experience [156]. Thermal stimuli have also been used to affectively augment text messages [212]. Temperature effectively altered the arousal of messages, particularly those with emotionally neutral content, and warmth was more arousing than cold.

Finally, recent work has also explored the affective properties of combining thermotactile stimuli with vibrotactile stimuli. Wilson *et al.* found that, when presented simultaneously, vibration dictated the arousal of the emergent stimuli, while the thermal component influenced valence, with warmer stimuli being more pleasant [230]. Yoo *et al.* found that a thermal component had the potential to enhance the emotional response to vibrotactile stimuli, finding that a pleasant stimuli presented alongside a constant cold 20°C stimulus was more pleasant and unpleasant vibrations alongside a 40°C stimulus was even more unpleasant [239]. The authors did note that the temperature levels used were significantly higher and lower than prior work and, in the case of the 40°C level, verged on pain threshold, which may have skewed results. Shetty *et al.* corroborated that constant temperatures had the potential to expand and emphasis existing affective ranges, but dynamic shifts in temperature were unpleasant [197]. Umair*et al.*'s qualitative approach found that both warm and cold temperatures could be pleasant based on their meaning to that participant, but that cold was more arousing and less-expected than warmth [216].

As can be seen, there is no clear picture of the affective properties of thermotactile stimuli, but it clearly has the potential to alter the valence and arousal of emotional experiences. The levels used, rate of change, and context of use all appear to be relevant factors and so any future work aiming to utilise this modality will require testing of its impact in that situation. The potential for thermal cues to impact emotional response, particularly valence, motivated Research Question 2 of this thesis. In particular, would thermotactile stimuli impact the resonance of emotionally resonant vibrations and how might that subsequently impact affective responses.

2.3.7 Social Robotics

Social robots can leverage a combination of different sensations, haptic and otherwise, to produce an emergent simulated social experience and provide examples more complex haptic interfaces which can produce meaningful and emotionally resonant affective experiences. These robots can deliver pleasant affective touch, not only by incorporating pleasant haptic stimuli like soft textures [223] and vibration [238], but also by emulating the social presence of a pet [94, 117, 223], leveraging the benefits of Animal-Assisted Therapy (AAT) which is not always practical or available. AAT has been shown to reduce blood pressure, stress [163] and anxiety [13] and, in a meta review of 49 studies, was found to be effective therapy for medical, behavioural and emotional difficulties [159].

There are several examples of social robots used in affective haptics and HCI research (see Figure 2.13). PARO the Seal [35, 198, 223] and Hudson *et al.*'s companion cat robot [94] have been used in care home settings, prompting residents to engage in pet-like social touch, reducing

Figure 2.13: Three examples of social robots which aim to emulate animal interaction. Left: PARO the seal, studied in care homes (extracted from [198]). Centre: The Haptic Creature, created to explore different haptic interactions with social robots [238]. Right: Companion robot cat also used in care homes [94].

feelings of loneliness and encouraging more social interaction between residents. There are concerns that robots imitating pets for the benefit of vulnerable users could be seen as demeaning [195], although research suggests that users do not share this concern, but rather worry about the socioeconomic availability of such devices [27].

Social robots have also been developed for pediatric settings. Arnold's Emobie prototype was designed as a soft tactile robot that acts as a companion for children in the hospital, express emotions to comfort them and providing a way for patients to log their emotions, but no evaluation was done [10]. Jeong *et al.*'s Huggable, a robot teddy bear which expresses emotion via animation, compared favourably to a plush toy and virtual avatar, facilitating positive and social interaction and potentially, therefore, patient outcomes [103].

Others have used social robots to specifically explore affective touch interactions. Chen *et al.* observed responses to robot-initiated touch delivered to the forearm and how this varied based on if the robot warned the participants and if the touch was intended to be affective or not [37]. Participants responded positively all conditions but preferred when not warned and when the touch was instrumental and not designed to be soothing. The Haptic Creature is a zoomorphic robot developed by Yohanan *et al.*, which utilised moving ears, simulated lungs and vibrotactile purring to effectively communicate its prescribed emotional state [236]. Participants found interactions with The Haptic Creature pleasant, although only slightly more when the creature attempted to express a positive emotional state than a negative emotional state [238]. Different touches users had with the robot were categorised by intent and users gravitated to pet-like touches, expecting the robot to respond appropriately [237].

Social robots demonstrate the ability for high fidelity social objects to use affective haptic elements to produce positive and meaningful emotional experiences [94, 198, 238] and multiple studies have shown the benefits they can have for individuals in stressful or lonely situations [103, 198, 223]. Animal-like robots like Paro or The Haptic Creature make use of shape, texture and haptic modalities to holistically simulate a meaningful emotional interaction which is already resonant with users' prior positive experiences; social touch with animals or pets. To achieve this, however, these robots are inflexible, large, non-discrete and adopt specific forms and behaviours that best simulate those prior pet interactions. This thesis explored if more flexible stimuli could still be resonant of prior emotional experiences and thus evoke emotional responses associated with those experiences, thus allowing some of the benefits of social robot interaction to be applied in a much wider range of contexts.

2.3.8 Emotional Resonance

Exploring affective haptics as a calming anxiety intervention using novel, 'emotionally resonant', vibrotactile stimuli is the core focus of this thesis. This thesis formally defines emotionally resonant stimuli as stimuli that evoke specific real-world experiences (such as feeling a cat purring or hearing running water) and subsequently elicit the associated emotional response the user has toward that experience. While using single vibrotactile actuators to achieve emotional resonance is a novel approach, using emotional resonance is not. The previous section discussed how social robots present themselves to users to evoke prior interaction with animals [94, 223, 237] and there are many other research examples of evoking prior experiences to elicit a specific emotional response.

Emotionally resonant sound has been effectively used to promote relaxation in a variety of contexts. In clinical settings, Tsuchiya *et al.* [215] and Arai *et al.* [8] asked participants to choose a soundscape they personally would find most relaxing from a selection of natural sounds (such as forest ambience, a small stream, or rain), both finding exposure to these sounds during surgery reduced pain and stress. Cutshall *et al.* achieved similar results by combining this approach with relaxing musical accompaniments, hypothesising that patients listening to their preferred soundscape could experience "a new perceptual reality so that the hospital environment is soothing and comforting" [49].

This approach of augmenting the users' perceptual reality with elements the user has a calming emotional response to has also been pursued in public settings. Natural sounds have been used to augment the soundscape of an urban city square, allowing participants to experience an "escape from usual busy life", perhaps indicating natural sounds were reminiscent of a less stressful countryside lifestyle [235]. Ogden *et al.* [164] and Valtchanov *et al.* [218] sought to use appropriate natural sounds to simulate natural environments in a zoo and VR respectively. Both found this resulted in calmer emotional responses. Finally, researchers testing different soundscapes as a sleeping aid for tinnitus patients found that sounds with emotional resonance played an important role of efficacy [81]. They also noted that sounds could have very different associations, such as the heartbeat which could be either a calm organic beat or elicit negative emotions due to prior emotional association ("the heart beat reminds me of horror films").

Affective haptic interfaces have also aimed to leverage the effects of emotional resonance. The Haptic Remembrance book was developed by Czech *et al.* to aid care home reminisce using a book with touch and audio displays tailored to each patient's past life events [50]. Israr *et al.*

worked with participants to define haptic patterns that represented real-world experiences on a vibrotactile array, which were then validated by a second group [99]. Similarly Shim *et al.* used a 2x2 vibrotactile array to display stimuli patterns representative of real-world phenomena, like bubbles or thunder, producing a wide range of emotional responses [199]. Mid-air ultrahaptic patterns have been in the same way, as Obrist *et al.* worked with users to define and validate emotionally resonant patterns [162] and later adopted by other researchers [69]. In their work on emotional response to texture, Iosifyan *et al.* noted that emotional associations with certain materials and real-world phenomena, such as granite and gravestones, impacted participant emotional response [98]. Thermal feedback can also be used to achieve emotional resonance, as Nakashige *et al.* observed presenting cold or hot stimuli alongside appropriate images of cold or hot food resulted more pleasant emotional responses [156].

The potential for utilise emotional resonance to produce positive, calming or pleasant emotional responses is clear. So far, however, research has utilised complex haptic interfaces (such as vibrotactile or ultrasonic arrays, multimodal interfaces or social robots) to successfully evoke real-world phenomena [162, 199, 238]. This limits the availability of such affective stimuli and in which settings they be can applied. Notably, the most prominent examples of applied emotionally resonant haptics are large and expensive social robots used primarily in medical care environments, like care homes [94, 198]. While vibrotactile devices have been used to simulate a heartbeat, which can successfully help users regulate emotion [11, 39, 43], this approach does not measure or leverage emotional response to the stimuli itself and it is unclear whether other sensations can be emulated. If simple vibrotactile actuators can be emotional resonance of other real-world phenomena, it could widen the range of emotional responses achievable by vibrotactile stimuli, and allow the the benefits of pleasant or calming emotionally resonant haptic stimuli to be utilised in a wider array of settings, such as during social exposure. Exploring this possibility is the focus of this thesis.

2.3.9 Summary

Various affective haptic modalities, including vibrotactile, thermotactile, ultrahaptics and texture, have demonstrated the ability to elicit high valence (pleasant) and low arousal (calming) emotional responses from users, both on their own and when combined with other modalities, although there are limitations. Human haptic perception is dependant on the type of stimuli and where on the body it is perceived. For example, glabrous skin, like that found on the palms and fingers, is more sensitive to both a wider range of vibration frequencies and to smaller changes in temperature. On the other hand, only hairy skin contains CT afferents, receptors which respond to stroking with a strong pleasant emotional response.

Of the investigated affective haptic modalities, vibration shows the broadest practical flexibility and applicability. Research has established foundational, although not conclusive, understanding of how variance of the basic wave parameters that impact emotional response. Additionally, combining several simple actuators into arrays has enabled the display of more meaningful, emergent stimuli patterns and vibrotactile actuators have long effectively augmented other devices, such as smartphones. Other modalities, like thermotactile and ultrahaptic interfaces, has also demonstrated the ability to elicit pleasant emotional response, but their size and form factor limited their applicability. Animal-like social robots face similar limitations, but highlight the level of meaningful emotional experience affective haptics can produce when able to tap in to the positive emotional resonance that users have with pets.

When considering how affective haptics could be used as a calming intervention in socially anxious settings, vibrotactile actuators are the most promising from a practicality perspective. Their small size allows them be to installed in discrete interfaces and used without prompting stigma or negative evaluation during social interaction, for example a user could be holding an innocuous item like a smartphone or wallet during conversation which is discretely presenting their hand with a calming vibrotactile stimulus. They do, however, suffer from a narrow range of previously observed emotional responses. One previously unexplored method of resolving this issue is leveraging emotional resonance to expand the affective range of vibrotactile stimuli. The ability for emotionally resonant stimuli to evoke pleasant and relaxing emotional responses has been demonstrated via social robots, ultrahaptics and vibrotactile arrays, but not single vibrotactile actuators. Exploring emotional resonance as a method to expand the affective range of vibrotactile stimuli could provide a novel calming intervention to help socially anxious users engage in social exposure, improving the accessibility of exposure therapy and improving their access to social spaces they otherwise find difficult to inhabit.

2.4 Literature Review Conclusions

Social anxiety is a prevalent and impactful mental health difficulty. Most psychotherapies which treat it involve an Exposure Therapy component; systematic exposure to social interactions, followed by discussions with a therapist to facilitate cognitive change. Exposure Therapy poses a significant adherence challenge for patients, however, as individuals with social anxiety experience heightened awareness of physiological anxiety symptoms and disproportionately interpret others social feedback as negative. While HCI research has developed interventions for anxiety disorders which could augment psychotherapy, there is a lack of interventions developed specifically for socially anxious users and their specific exposure therapy requirements.

Affective haptics offers an ideal method of providing a calming emotional intervention to users during social exposure, as it can be delivered discretely and without occupying conversational faculties, such as eye-contact, hearing or voice. Affective haptics encompasses a wide variety of modalities, each with varying emotional responses. Applications of affective haptics such as social robots and vibrotactile arrays have succeeded in creating pleasant and calming emotional experiences, leveraging emotional resonance to evoke known pleasant sensations like social pet interaction, or by triggering CT afferents with simulated stroking. They suffer from limitations, however, lacking availability and being distinctly non-discrete, risking the invitation of stigma and negative social evaluation during use. Single vibrotactile actuators are the most accessible and widely applicable affective haptic interface, but their emotional response range is more limited. If emotional resonance could be leveraged to expand their emotional range, this could provide calming affective touch in unprecedented settings.

Can single vibrotactile stimuli be emotionally resonant? If so, how is their design and application informed by the experiences and requirements of socially anxious users? Finally, does this result in an effective calming intervention for social exposure?

The literature discussed in this review lays the necessary foundations for the research questions of the thesis. By understanding social anxiety, how it is treated and what interventions HCI has previously contributed, the potential of affective haptics as an exposure therapy intervention was recognised. Then, by considering the ground already covered by affective haptics research and the strengths and limitations of different modalities, vibrotactile stimuli where chosen for their ability to intervene discretely in social exposure settings and emotional resonance identified as a novel method to expand its otherwise limited range of emotional responses. Research questions necessary to pursue this novel line of discovery were created and developed as informed by findings over the course of the project:

Research Question 1: *Can single-actuator vibrotactile stimuli be emotionally resonant of real-world sensations?*
Research Question 1 will determine if vibrotactile stimuli delivered by a single actuator can be emotionally resonant, enabling them to elicit a wider range of emotional responses by leveraging emotional associations with real-world phenomena. This is a foundational requirement before any subsequent social anxiety intervention can be developed.

Research Question 2: *Can thermal cues be used to enhance the emotional resonance and affective range of vibrotactile stimuli?*
Research Question 2 aims to understand how the addition of thermal cues impacts both the affective responses to emotionally resonant vibrotactile stimuli and the emotional resonance of specific stimuli with an associated temperature. Prior work suggested a significant interaction between the two modalities [230] and there may be some effect on emotional resonance or response when different temperatures are presented alongside appropriate or dissonant stimuli [156].

Research Question 3: *Which calming real-world experiences would users prefer emotionally resonant vibrotactile stimuli to evoke and what factors impact their use in social settings?*
Following the development of an initial set of emotionally resonant vibrotactile stimuli, research

focuses on the how these stimuli could best meet the requirements of socially anxious users. Research Question 3 will be answered by bringing users into the design process to understand the challenges faced by socially anxious people, how they currently cope with social exposure and which calming emotional experiences could be emulated by emotionally resonant vibrotactile stimuli, informing testing an expanded set. Additionally, the impact of other factors on user preference, such as different social settings, texture and form factor will be explored.

Research Question 4: *Can emotionally resonant vibrotactile stimuli calm socially anxious users during social exposure?*
Finally, Research Question 4 will measure the efficacy of this novel approach. Findings from the preceding studies will inform the design of an emotionally resonant vibrotactile intervention built with consideration of the experiences and requirements of socially anxious users. It will then be utilised by a treatment group of target participants undergoing a social exposure task and the results compared with a control group to observe any significant effect on anxiety response.

Chapter 3

Emotionally Resonant Vibrotactile Stimuli

3.1 Introduction

Vibrotactile stimuli are ideally placed as a calming *in vivo* social anxiety exposure therapy intervention, being usable without interrupting conversation and able to discretely augment handheld objects or devices. They have a key limitation, however. Prior research has observed a narrow range of emotional responses to vibrotactile stimuli, particularly on the valence axis of the circumplex model. Emotional resonance has been successfully employed in other haptic or auditory applications to elicit calming and pleasant emotional responses, but emotionally resonant vibrotactile stimuli have not been assessed. Therefore, a series of experiments was conducted to establish if emotional resonance could be leveraged to expand the emotional range of vibrotactile stimuli and deliver calming and pleasant emotional experiences which could be utilised in socially anxious settings.

This chapter discusses three experiments which investigate the affective properties of novel vibrotactile stimuli presented via a single actuator. The first experiment investigates the effects of the elongated duration required for more complex, meaningful stimuli on emotional response, and the second and third experiments follow on to explore emotional response to emotionally resonant vibrotactile stimuli. The third experiment combines these stimuli with thermal cues to ascertain the impact of possible interaction effects which could further enhance emotional response range. The experiments in this chapter were designed to answer Research Questions 1 and 2:

RQ1: Can single-actuator vibrotactile stimuli be emotionally resonant of real-world sensations?

RQ2: Can thermal cues be used to enhance the emotional resonance and affective range of vibrotactile stimuli?

Each experiment's findings will be discussed in regards to these research questions, both during each experiment section and in the conclusion to the overall chapter.

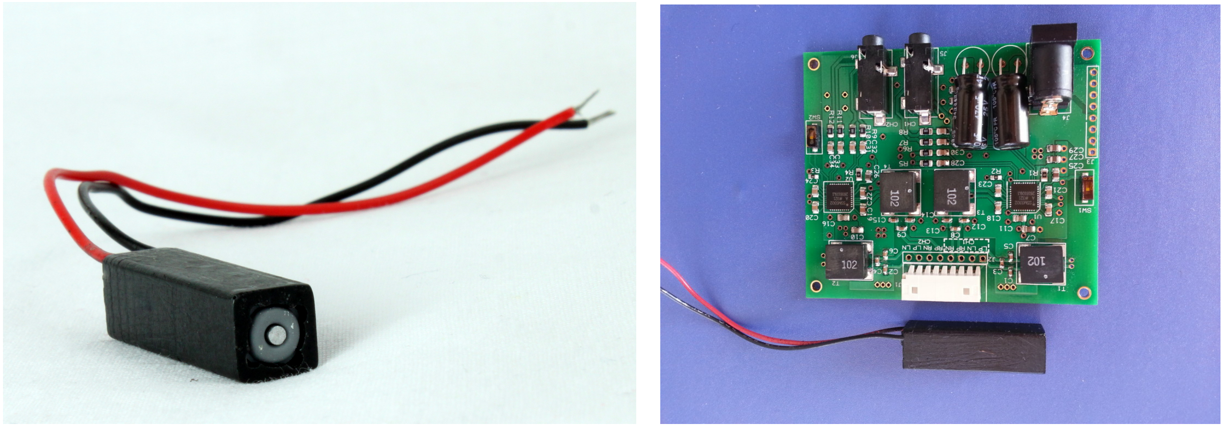


Figure 3.1: The Haptuator Mark II, the vibrotactile actuator used throughout the project to convey stimuli, and the Haptu-Amp-Quad amplifier used to power it (extracted from manufacturer's website: *tactilelabs.com*).

3.2 Experiment 1: Effects of Increased Duration on the Affective Properties of Tactons

The first experiment of the project served two aims. When creating vibrotactile stimuli which are evocative of real-world phenomena, the stimuli will require a longer duration than the 0.2-2 second Tacton-like cues used in prior affective haptic research to accommodate the time it takes natural phenomena like crashing waves, breathing cycles or cat purring to occur and be perceived. The first aim was, therefore, to study if significantly increasing the duration of previously studied Tactons to twenty seconds would impact emotional response. Secondly, this study also provided an opportunity to trial the apparatus, laboratory set-up and emotional response measurement intended for use in the future.

3.2.1 Apparatus

The same apparatus and set-up were used for both Experiment 1 and 2. Vibrotactile stimuli were delivered via a Haptuator Mark II, powered by a Haptu-Amp-Quad (both produced by Tactile Labs [A.1, A.2]) and driven via audio output from a 3.5mm jack (see Figure 3.1). The Haptuator Mark II can present 98% of perceivable haptic bandwidth (between 10Hz-7kHz) and has been used in prior work by Wilson *et al.* [230], allowing for direct comparison to their work.

The Haptuator was mounted to the centre of the internal side of the rigid cap of a Thermos Flask (see Figure 3.2). Participants then rested their palm side of the hand on top of the cap and their fingers around the sides, allowing vibration radiating through the rigid cap to be presented to the majority of the palmar side of the hand. The cap's orientation relative to the table was fixed so that the internal Haptuator was positioned perpendicularly to the edge of the desk, preventing the risk of orientation changes causing perceived intensity variance [97,230]. The internal space and hole at the bottom of the flask cap were then filled with foam sheets, masking residual noise and providing a non-rigid base which prevented the cap from transmitting vibration to the tabletop and causing rattling or movement. Additionally, headphones playing brown noise were used to block any remaining residual sound. The laptop used was a 2018 13" 2.3GHz Core i5 MacBook Pro, with its internal volume level set to 6, was used to provide input to the amplifier and allow participants to self-report measures when prompted.

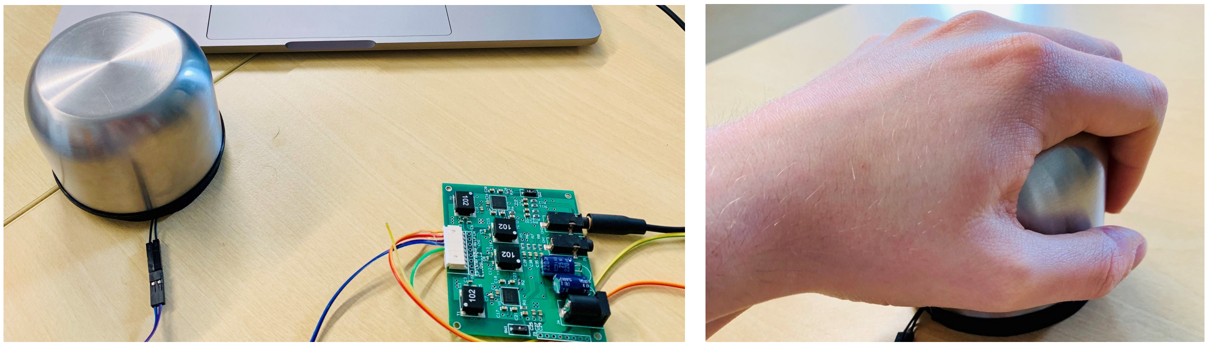


Figure 3.2: Experimental apparatus used in Experiment 1 and 2. A Haptuator Mark II was mounted inside the metal flask cap. It was connected to a laptop via an Haptu-Amp-Quad. Participants were asked to rest their hand on the flask cap so that it filled their hand as shown.

3.2.2 Methodology

This was a within-subjects experiment designed to assess the impact of an elongated duration on emotional response to pre-existing vibrotactile stimuli. The study featured three independent variables: stimulus carrier frequency, amplitude and duration. The three levels used each for frequency and amplitude replicated those used in prior work [230, 240] (see Table 3.1 for independent variable levels). Nine different vibrotactile stimuli were used, resulting from every unique combination of the frequency and amplitude. These nine stimuli were them presented at two duration levels: a short two second Tacton length and an elongated twenty second length, for a total of eighteen stimuli. There were two dependent variables: participant self reported valence and arousal, which are used to plot emotional response on Russel's Circumplex Model of Affect [184]. Details on how these measures were collected are given in the next section.

Parameter	**Values**			**A1**	**A2**	**A3**
Amplitude	A1,A2,A3		*90Hz*	1.7g	3.3g	4.3g
Frequency (Hz)	90,200,300		*200Hz*	0.6g	1.0g	1.3g
Duration (s)	2,20		*300Hz*	0.9g	1.2g	2.2g

Table 3.1: Independent Variable levels used to generate eighteen different stimuli in Experiment 1. Amplitude levels were adjusted for different levels of frequency to normalise perceived intensity [230] (g = gravitational acceleration).

While prior studies used shorter duration levels of one second or less, they repeated the stimuli three times in succession. It would be impractical to present twenty second stimuli thrice in quick succession in this experiment, as elongated exposure to long stimuli would result in both sensation-reducing adaptation and become irritating in an experiment context as participants experience the same stimuli almost uninterrupted for a whole minute. Therefore, in order to retain the same procedure for participants when experiencing either long or short stimuli, stimuli were presented once each and the minimum duration level was increased to two seconds to compensate for the lack of repetition. Twenty seconds was selected based on feedback from pilot participants who found longer stimuli frustrating or boring to experience in an experimental context. While, in prior studies, a higher duration resulted in higher arousal, it was expected that a duration level of twenty seconds would result in significantly lower arousal than a duration of two seconds, due to adaptation. The shorter two second stimuli were expected to behave similarly to those used in the prior studies which used the same actuator, frequency and amplitude levels [230, 240]. Therefore, the study had two hypotheses:

H1: Vibrotactile stimuli with a duration of 20 seconds elicit a lower arousal response than those with a duration of 2 seconds;

H2: Emotional responses to 2 second vibrotactile stimuli will be similar those found in prior work using the same frequency and amplitude levels.

3.2.3 Participants

Participants were recruited via university campus advertisements, the School of Computing Science experiment recruitment mailing lists and social media. Participants were required to be age eighteen or over and had no impediment to their haptic perception. 20 participants were recruited (10 male, 10 female) and took part in the experiment, which lasted approximately 20 minutes per person.

3.2.4 Procedure

Participants were paid £6 for their time. The experiment took place in a small room in the School of Computing Science with a table holding all the apparatus and chairs for the participant and experimenter. Participants were asked to read an information sheet and then sign a consent form before proceeding with the experiment (see Appendix for these documents [B.1.1, B.1.2]).

The experiment was comprised of two tasks. In the first, participants experienced all nine of the two second stimuli, presented in a random order until each stimulus had been experienced twice. After each stimulus was presented, a sequence of two pop-up windows, each containing a 7-point Likert scale, appeared on the laptop, asking participants to rate the stimulus in terms of valence and arousal, where the far left point of the scale was labelled as 'Low Arousal/Valence' and the far right point was labelled as 'High Arousal/Valence'. Arousal and valence were both defined and explain for each participant before rating. Responses were encoded as either '-3', '-2', '-1', '0', '1', '2' or '3', with negative numbers assigned to the low half of the scale and *vice versa*. After the first task ended, participants took a short five minutes break, then proceeded to the second. The second task was identical except that it featured exclusively the 9 20-second stimuli, again presented in a random order until all were presented twice. Throughout both tasks participants wore headphones playing brown noise to obfuscate any residual background noise from Haptuator. Once both tasks were complete, participants were asked about their experiences with the stimuli in a semi-structured interview regarding how they perceived different stimuli:

1. *Did you find any of the vibrations more or less alerting than others? If so, was there a pattern?*

2. *Did you find any of the vibrations more or less pleasant than others? If so, was there a pattern?*

3. *Did you notice a difference in your response to longer vibrations, when compared to the shorter vibrations??*

4. *Do you have any other comments or thoughts on the experiment and the sensations you experienced?*

The rationale for separating the duration levels by task was to allow participants to more easily compare the set of short stimuli and set of long stimuli with each other during qualitative discussion.

3.2.5 Results

Methodology

Statistical analysis of the results of all the experiments in this thesis was conducted using R[1] and the pertinent analysis scripts and data can be found in the University of Glasgow's Enlighten database[2]. In this experiment and throughout the thesis, non-parametric self-reported Likert Scale data were collected. Non-parametric tests such as the one-way Kruskal-Wallis test, Mann-Whitney U test, Friedman test, or Wilcoxon signed-rank test, do not allow multi-factor analysis, unlike parametric testing. To conduct effective multi-factor analysis on these data using traditional parametric tests, the Aligned Rank Transform (ART) was utilised [56, 101]. Conover and Iman's original rank transform procedure [42] replaces data observations of a variable with its respective rank compared to other observations, and the subsequent data can then be subject to parametric tests. It can, however, inflate Type I errors for interactions effects [101]. The

[1]The R project for Statistical Computing. https://www.r-project.org

[2]University of Glasgow - Research - Enlighten. https://www.gla.ac.uk/research/enlighten/

ART first 'aligns' the data before ranking, meaning that, when testing for an interaction effect, all other effects are stripped out, leaving only pertinent data. This can then be ranked and be subjected to parametric testing. Using the ART allowed multi-factor analysis of non-parametric data. The R package *ARTool*[3] was used to conduct this procedure when required throughout the thesis.

Main Effects and Interaction Effects of Duration, Frequency and Amplitude

A series of six two-factor ANOVA tests were performed. Three searched for main and interaction effects on valence from the possible pairs of independent variables: duration - amplitude, duration - frequency and amplitude - frequency, once each pair was subject to the Aligned Rank Transformation. The other three ANOVA searched for any effects of the same variable pairs upon arousal (see Table 3.2).

This experiment was most concerned in ascertaining the possible ramifications of a much longer stimulus duration on emotional response, but there was no main effect of duration on arousal or valence. The ANOVAs did, however, find an interaction effect between duration and frequency upon valence ($F = 3.06, p < 0.05$). Following this, Chi-Squared Test interaction analysis with Holm-Bonferroni correction was performed [93] using the R package *phia* [182]. This analysis found a significant difference ($\chi^2 = 5.7851, p < 0.05$) between how participants rated the valence of 2 second and 20 second stimuli at 90Hz and 200Hz. At 90Hz, the lower frequency level, participants felt that two second cues were more pleasant than twenty second cues, but at a higher frequency of 200Hz participants found the longer twenty second stimuli and their shorter two second counterparts similarly pleasant (see Figure 3.3).

Amplitude had a significant main effect on arousal ($F = 63.43, p < 0.001$) and on valence (Increased amplitude levels lead to increased arousal and decreased valence responses, the same finding as found by previous work with the same or similar stimuli [85, 230, 240]. Frequency had a significant main effect on arousal ($F = 46.81, p < 0.001$), but no effect on valence. Increasing frequency led to decreased arousal, echoing general findings by Hasegawa *et al.* [85] but contradicted results by Wilson *et al.* [230] and Yoo *et al.* [240] using the similar stimuli. Mean emotional responses to this stimuli set following expected trends from prior work, with the stimuli set exhibiting a narrow emotional range, particularly on the valence axis (see Figure 3.4 and Table 3.3). This reinforces the need to meaningfully expand the affective range of single-actuator vibrotactile stimuli if they are to be used in varied emotionally meaningful interfaces. Following up on the significant main effects found by the ANOVAs, *post hoc* analysis was conducted.

[3] Aligned rank transform [R package ARTool version 0.11.1] https://cran.r-project.org/web/packages/ARTool/index.html

Duration / Frequency Main Effects on Arousal	F	Df	P.Value
Duration	4.498	1	**0.0347**
Frequency	36.26	2	**<0.0001**
Duration / Frequency	2.772	2	0.0639
Duration / Amplitude Main Effects on Arousal	**F**	**Df**	**P.Value**
Duration	1.747	1	0.1871
Amplitude	47.18	2	**<0.0001**
Duration / Amplitude	0.068	2	0.9342
Frequency / Amplitude Main Effects on Arousal	**F**	**Df**	**P.Value**
Frequency	46.82	2	**<0.0001**
Amplitude	63.43	2	**<0.0001**
Frequency / Amplitude	5.038	4	**0.0006**
Duration / Frequency Main Effects on Valence	**F**	**Df**	**P.Value**
Duration	0.318	1	0.5729
Frequency	2.538	2	0.0805
Duration / Frequency	3.060	2	**0.0482**
Duration / Amplitude Main Effects on Valence	**F**	**Df**	**P.Value**
Duration	0.062	1	0.8034
Amplitude	10.73	2	**<0.0001**
Duration / Amplitude	0.753	2	0.4714
Frequency / Amplitude Main Effects on Valence	**F**	**Df**	**P.Value**
Frequency	2.551	2	0.0795
Amplitude	10.85	2	**<0.0001**
Frequency / Amplitude	0.529	4	0.7145

Table 3.2: Experiment 1 main effects of duration, amplitude and frequency on arousal and valence. P values which indicated significant main effects and interactions effects are marked in bold.

	Amplitude			**Frequency (Hz)**			**Duration (s)**	
	A1	**A2**	**A3**	**90**	**200**	**300**	**2**	**20**
Valence	0.66	0.54	0.03	0.37	0.62	0.24	0.42	0.39
Arousal	-0.70	0.10	0.87	0.88	-0.35	-0.26	0.00	0.18

Table 3.3: Mean valence and arousal responses (rated on a Likert scale of +3 to -3) for each in dependent variable level in Experiment 1.

Post Hoc Analysis

Single factor *post hoc* analysis was conducted using the R package *emmeans* [124] with Tukey P value adjustment. Pairwise comparisons of the three amplitude levels found that valence responses to the highest amplitude level were significantly lower when compared to the other two (see Table 3.2.5). When tested for effects on arousal responses, consistent significant differences

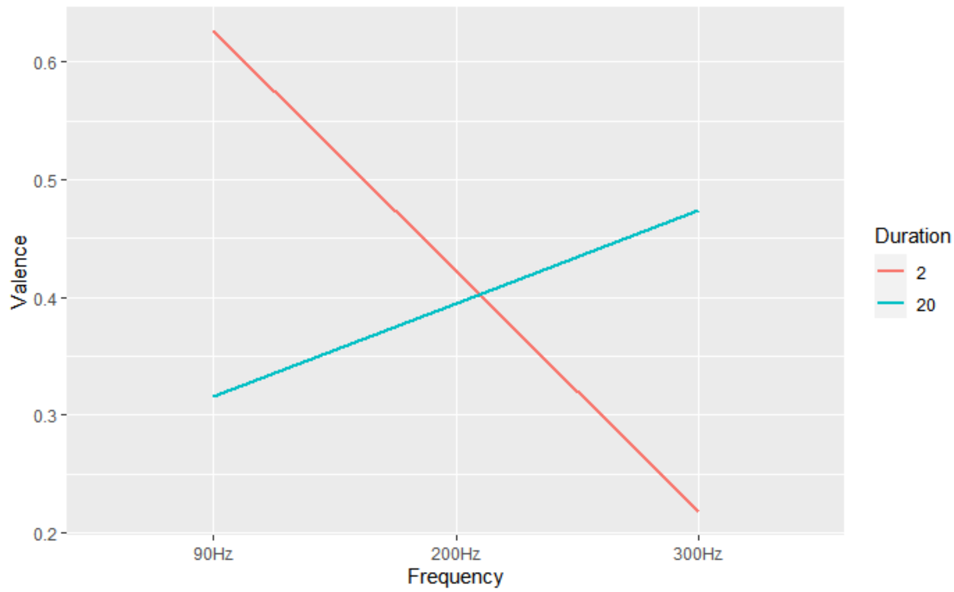


Figure 3.3: Interaction plot showing the average valence for 2 and 20 second stimuli for each level of frequency. Participants reported that 2 second cues were significantly more pleasant than 20 cues at 90Hz, but felt the opposite at 300Hz.

were found between all three amplitude level pairs. In all three pairs, a higher amplitude level resulted in a higher arousal responses.

When investigating frequency's effect on arousal, significant differences were found between the lowest level of 90Hz and both 200Hz and 300Hz. In both cases, participants rated the arousal of the lower, 'rougher' 90Hz higher than the other two higher levels.

Qualitative Feedback

After the experiment each participant was asked four questions to which they could give open-ended answers. Answers were grouped by recurring topics and sentiments.

Question 1: Did you find any of the vibrations more or less alerting than others? If so, was there a pattern?

The most mentioned factor was frequency. Nineteen participants cited frequency affecting arousal, but there was no strong consensus, as eleven people felt higher, smoother frequencies caused more arousal but eight others felt that lower, rougher frequencies had this effect. This contrasts the quantitative results which found lower frequencies significantly more arousing. Twelve participants felt a higher amplitude, or a 'stronger' stimulus, resulting in higher arousal, which corroborates the data.

Question 2: Did you find any of the vibrations more or less pleasant than others? If so, was there a pattern?

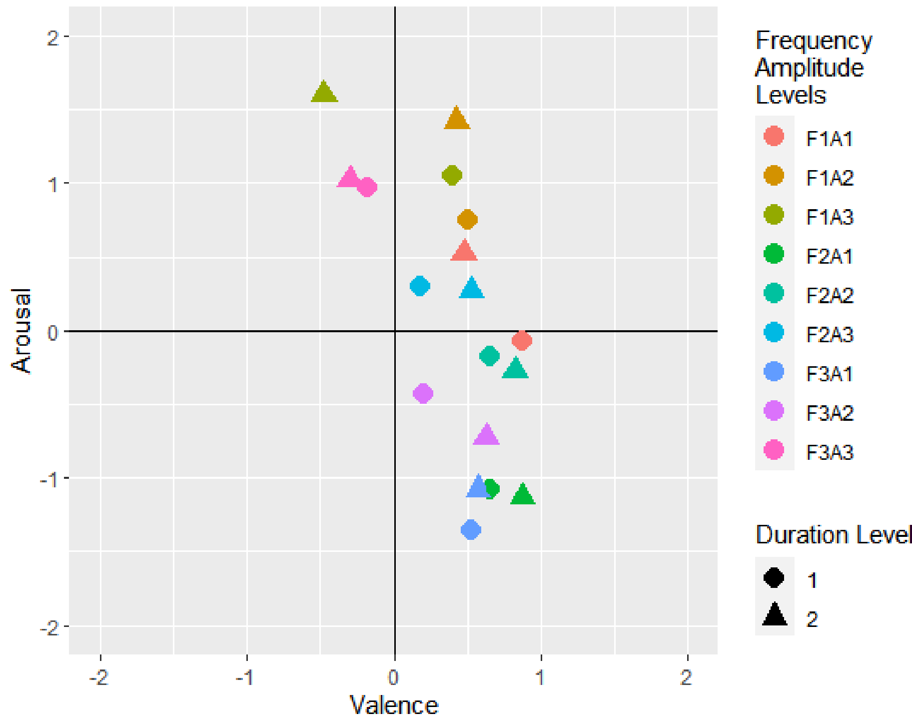


Figure 3.4: Valence - Arousal plot showing each stimulus as a combination of frequency and amplitude plotted by its mean emotional response, with short and long duration levels plotted separately. Valence and arousal were reported on a +3 to -3 Likert Scale, so it should be noted this plot is limited to a +2 to -2 range for clarity.

Amplitude Valence Contrasts	Effect Size	Estimate	T.Ratio	P.Value
A1 - A2	0.0541	5.070	0.419	0.9079
A1 - A3	0.5458	51.16	4.228	**0.0001**
A2 - A3	0.4917	46.09	38.09	**0.0005**
Amplitude Arousal Contrasts	**Effect Size**	**Estimate**	**T.Ratio**	**P.Value**
A1 - A2	-0.688	-56.20	-5.328	**<0.0001**
A1 - A3	-1.453	-118.7	-11.26	**<0.0001**
A2 - A3	-0.766	-62.50	-5.930	**<0.0001**
Frequency Arousal Contrasts	**Effect Size**	**Estimate**	**T.Ratio**	**P.Value**
90Hz - 200Hz	1.100	92.81	8.522	**<0.0001**
90Hz - 300Hz	1.063	89.64	8.231	**<0.0001**
200Hz - 300Hz	-0.037	-3.170	-0.291	0.9545

Table 3.4: Pairwise contrasts between amplitude and frequency levels found when estimating differences in marginal mean arousal and valence responses in Experiment 1. Contrasts with significant differences are indicated with bold p values. Effect size reflects Cohen's D, the standardised difference of means between the first and second stimulus. Positive effect sizes indicate the first stimulus in the pair had higher arousal or valence responses and *vice versa*.

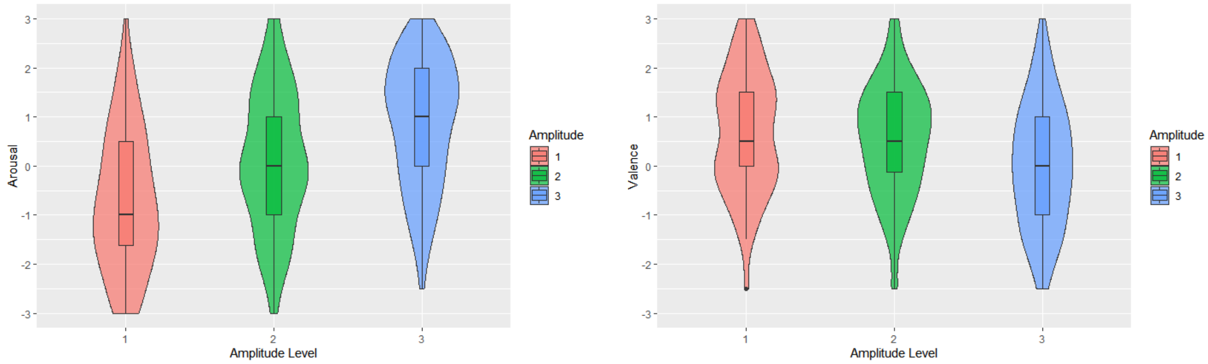


Figure 3.5: Violin plots showing distribution density and the median and interquartile arousal and valence responses at each amplitude level.

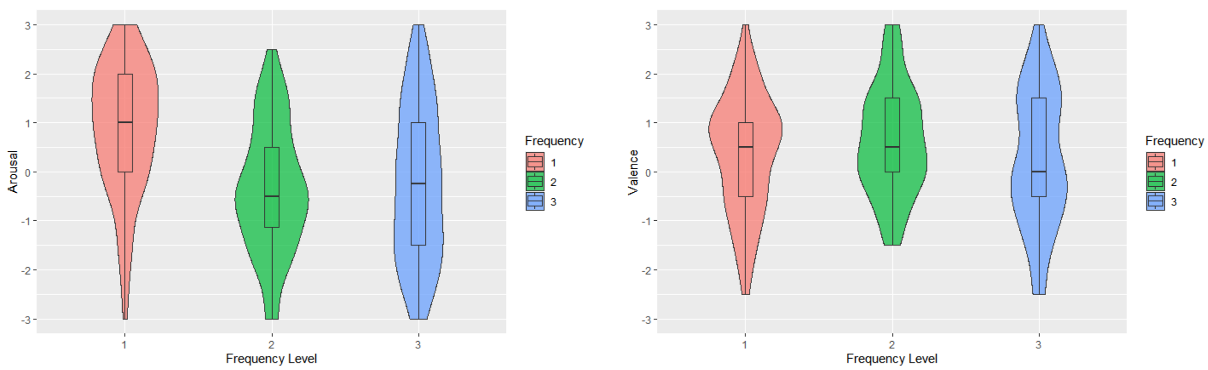


Figure 3.6: Violin plots showing distribution density and the median and interquartile arousal and valence responses at each frequency level.

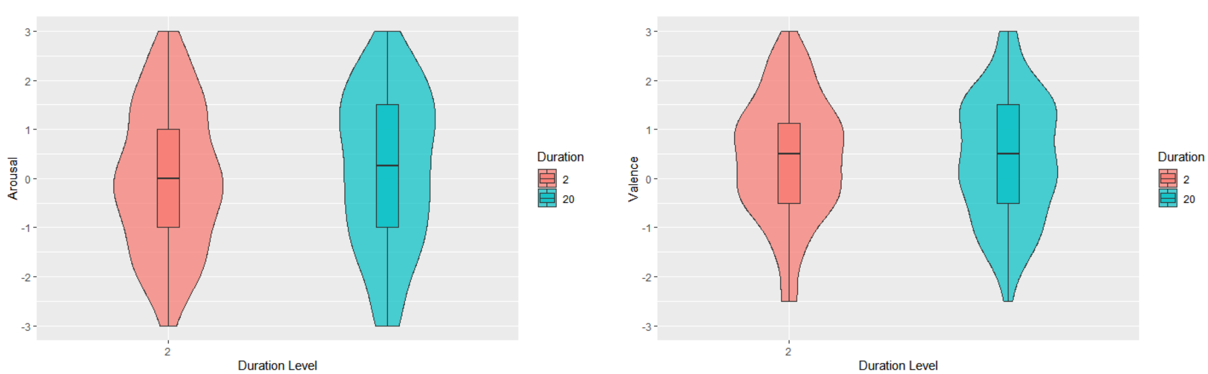


Figure 3.7: Violin plots showing distribution density and the median and interquartile arousal and valence responses at both duration levels.

The most mentioned variable that participants felt affected the pleasantness of stimuli was frequency, despite it having no statistically significant effect. This was perhaps because the fourteen participants who mentioned it were exactly divided on sentiment, with seven each believing that higher or lower frequencies made the stimuli more pleasant. Six participants mentioned amplitude, with four stating that softer stimuli were more pleasant and two stating that stronger were more pleasant. Two participants mentioned that soft stimuli reminded them of massage, although they each cited low and high frequency respectively was required to achieve this effect.

Question 3: Did you notice a difference in your response to longer vibrations, when compared to the shorter vibrations?

The topics raised by participants regarding the effects of duration were varied and no single topic was mentioned by more than seven people. Participants mentioned a variety of adverse effects while experiencing the longer stimuli. Seven people felt the sensation in their hand deadened towards the end of the twenty second stimuli, suggesting they were suffering from haptic adaptation as discussed in Section 2.3.2. Most participants described this effect starting around halfway through the stimulus's duration, between eight and twelve seconds. Four people mentioned that they found waiting for a full twenty seconds annoying and three participants said they lost concentration or "zoned out" during longer stimuli. Some positive effects of a longer duration were also raised. Six participants noted that the longer duration allowed them to better understand or perceive stimuli while five participants felt longer stimuli were more pleasant.

Question 4: Do you have any other comments or thoughts on the experiment and the sensations you experienced?

Seven participants had further comments to add. Three participants felt that shorter stimuli would be more useful to alerts of notifications due to the appropriate length and two people commented they may have found the longer stimuli less annoying if they knew why they were long and another felt if they had something else to go or experience while experiencing longer stimuli they may find them less irritating. The feeling of losing sensation or concentration on longer stimuli was reiterated by two participants. Finally one participant suggested putting a more 'organic vibration' inside of plushie.

3.2.6 Discussion

The first experiment assessed the impact on affective response when extending the duration of previously studied stimuli beyond the 0.2-2 second range used in prior work. Additionally, it also provided an opportunity to become familiar with the apparatus and measures planned for use in future studies.

Hypothesis 1 Discussion

In prior work stimuli with a longer duration tended to have higher arousal ratings. The longer stimuli tended to be a maximum of one or two seconds in length [197, 230, 240]. When observing responses to a much longer uninterrupted duration level of 20 seconds, it was hypothesised that the familiarity participants would gain with the stimuli over the duration and the potential sensory deadening effect of haptic adaptation would lead to lower arousal responses. Despite this expectation, there was no main effect of duration on arousal or valence. The lack of main or interaction effects on arousal means Hypothesis 1 can be rejected. It may indicate that longer stimuli can be used in future studies without a confounding effect on valence or arousal. This would, however, disregard the common concerns about longer stimuli raised in qualitative feedback. Twelve comments made by the twenty participants raised concerns that, when experiencing longer stimuli, either their haptic perception deadened or they lost their ability to focus on the sensation. Additionally, in an experimental context where participants are experiencing many stimuli in sequence, waiting for a stimulus to finish after already comprehending it could be cause boredom and frustration that alters emotional response ratings. Given these concerns, the decision was made to reduce the stimuli duration for future studies to ten seconds. This should allow for the benefits of better comprehension, especially for stimuli with more complex patterns drawn from organic sounds, while curtailing the issues participants reported beginning to experience halfway through the twenty second stimuli during Experiment 1.

Hypothesis 2 Discussion

This experiment used a set of stimuli used in two prior works [230, 240] and similar to those used in other related work [85], thus it was pertinent to observe if participant emotional responses to this stimuli set followed established prior trends. If there was a significant deviation, it could indicate that the apparatus or experimental procedure used in Experiment 1 were having a confounding effect. Therefore it was hypothesised that the emotional responses to the shorter two-second stimuli would be similar to those found by prior work. The positive effect of amplitude on arousal and and negative effect on valence did echo the findings of prior work, although unlike the researchers using this stimuli set, Wilson *et al.* and Yoo *et al.*, this study found increasing frequency had a negative effect on arousal, echoing findings from Hasegawa *et al.* This could be attributed to the interaction effect between frequency and duration on valence (which found that shorter stimuli had higher valence at 90Hz than they did at 200Hz when compared to longer stimuli). Both past work and this study found that stimuli with lower valence tended to have higher arousal, and *vice versa*. The interaction effect finding that short stimuli have lower valence at higher frequencies is not incompatible with findings of related work on exclusively short stimuli that higher frequencies resulted in higher arousal. The interaction effect suggests that the effects of frequency on arousal found in these prior works did not hold up over a combined set of short and long stimuli. While these results do not allow Hypothesis 2 to be fully upheld, they did not present a problematic departure from prior affective haptic research results, particularly when considering the interaction of duration on divergent findings.

The results of this experiment directly informed the duration level used for stimuli in all subsequent experiments. Understanding the possible ramifications of affective vibrotactile cues far longer than those studied prior to this research was a necessary prerequisite before developing longer, more complex stimuli evocative of real-world sensations in pursuit of addressing Research Question 1: *Can single-actuator vibrotactile stimuli be emotionally resonant of real-world sensations?* With this investigation into duration complete, and the efficacy of the apparatus and measures confirmed, a second experiment followed which to investigate Research Question 1 by observing affective responses to novel vibrotactile stimuli designed to be emotionally resonant.

3.3 Experiment 2: Emotionally Resonant Vibrotactile Stimuli

This experiment investigated emotionally resonant vibrotactile stimuli. Emotionally resonant experiences have shown potential to be calming and pleasant in the fields of social robotics [94,223,237] and affective sound [8,49,215]. If vibrotactile stimuli can be emotionally resonant, it could prompt a wider range of meaningful emotional responses from users than the narrow range observed in prior work with abstract waveforms. A set of eight stimuli generated from the sound recordings of recognisable real-world haptic and auditory phenomena were tested both with and without identification and each participant's emotional responses to all the stimuli were recorded. Explanation and justification of stimuli is detailed in Section 3.3.2.

Figure 3.8: Emotionally resonant stimuli evoke real-world sensations. A user's emotional response to a stimulus may be similar to their emotional response to the original real-life sensation it evokes. For example, experiencing a vibrotactile stimulus reminiscent of cat purring may remind the user of past experiences with cats and their associated emotions with those experiences.

3.3.1 Methodology

This was a within-subjects experiment designed to observe emotional responses to stimuli generated from the sounds of real-world phenomena presented both with and without identification, as well as elicit qualitative feedback regarding how emotionally resonant participants found the different stimuli. The study featured two independent variables: stimulus presented (which of the eight stimuli was last presented to the participant) and identification (was the identity of the stimuli the participant just experienced given to the participant before they reported emotional response). The apparatus used was identical to Experiment 1. Details around the stimuli chosen and how they were processed can be found in the next section.

There were three dependent variables: self-reported valence and arousal, and recognition accuracy (whether the participant correctly recognised the stimuli presented when not given their identity). Observing how accurately participants could identify unknown stimuli would inform if participants found certain stimuli more resonant with their original sensation or simpler distinctive compared to the rest of the set. Comparing stimuli experienced with and without identification would show if having knowledge of a stimulus's identity contributed positively to the participants' emotional responses and how if they were able to better associate the stimulus to the sensation it evoked.

This study had three hypotheses.

H1: Emotionally resonant stimuli will exhibit a wider range of valence responses than abstract stimuli;

H2: Participants will find stimuli emotionally resonant if they had a prior emotional association with the sensation evoked;

H3: Stimuli whose identity is given or consistently accurately identified will have higher valence and be more emotionally resonant.

It was hypothesised that there would be a wider range of emotional responses, particularly on the valence axis, to emotionally resonant vibrotactile stimuli, hence H1. H2 addressed the question, core to Research Question 1, of whether participants could find vibrotactile stimuli emotionally resonant with their prior experience. H3 follows on from the prior discussion of the impact whether stimuli were recognised or identified. It was expected that participants would find identified stimuli would be more emotionally resonant and that subsequently they would also find them more pleasant than stimuli which were unidentified and had low recognition rates.

3.3.2 Stimuli

Vibrotactile stimuli were produced from sound recordings of real-world phenomena. Using original sound recordings guaranteed the rhythm and cadence of the bass frequencies presented by the Haptuator were, by definition, identical to the real world phenomena that was recorded. This meant that for phenomena which are either experienced by touch (examples from this experiment include *Cat Purring* and *Underwater Bubbles*), or heard (e.g. *Babbling Brook* and *Crashing Waves*), participants were given the opportunity to recognise the rhythm and cadence of the vibrotactile stimuli which exactly matched a real recorded example of that phenomena. An alternative method could have been to create new stimuli which correctly evoke real-world phenomena. This would, however, require significant iteration and strong validation to confirm that the stimuli were representative of natural sensations.

A key limitation of this presenting sound recordings via vibration is that higher frequency details will not display effectively. It should be noted, however, that this frequency range limitation would also apply to custom-made artificial stimuli which would also need to be designed to be resonant of natural phenomena with only lower frequencies. Thus, this experiment assessed if participants could recognise stimuli generated from different real-world sensations, or find these stimuli emotionally resonant, when the exact rhythm and cadence of these sensations' lower frequencies is presented via a vibrotactile actuator. If so, would participants have a similar emotional response to the stimulus that they would to the original sensation?

Eight stimuli generated from sound recordings of real-world phenomena were used in this experiment: *Heartbeat*, *Cat Purring*, *Slow Breathing*, *Underwater Bubbles*, *Crashing Waves*, *Rustling Leaves*, *Babbling Brook* and *Muffled Conversation*. In this study, these stimuli were implemented following a process where sounds which embodied calming experiences found in prior affective sound or touch research were tested in an exploratory fashion for clarity of presentation through the Haptuator. Eight stimuli which evoked calming sensations from prior work and could be effectively presented were used. The first four (*Heartbeat*, *Cat Purring*, *Slow Breathing*, *Underwater Bubbles*) were chosen because they are sound phenomena which already have a haptic component in real world perception and so may adapt well to being presented with affective haptics. The latter four (*Crashing Waves*, *Rustling Leaves*, *Babbling Brook* and *Muffled Conversation*) were sounds which achieved calming emotional resonance in prior affective audio studies [8, 49, 218, 235]. Recordings with a relaxed breathing rate (12 breaths per minute) and heartbeat (60 beats per minute) were chosen.

The raw sound files were sourced from Freesound.org[4], a collaborative database of user-submitted audio samples and recordings. Most sounds had multiple possible records available on this database, from which pilot testing was used to select the best presenting sound file. The sound files specifically used can be found in the University of Glasgow Enlighten database.
The audio recordings used in this study were under a creative commons public domain licence and free to use without condition. Processing was then used to normalise the strength of presentation between different recordings when presented using the Haptuator, as these recordings of natural phenomena varied in volume at different frequencies. First, each stimulus' volume was

[4]Freesound https://freesound.org/help/about/

normalised to 89dB using the program MP3Gain [5], following iterative pilot testing. Second, the base frequency range (0-100Hz) of five stimuli were amplified using Audacity[6] in increments of 15dB until they presented at a similar intensity to the unchanged stimuli in the set. The bass frequencies of *Slow Breathing*, *Babbling Brook* and *Crashing Waves* were amplified by 15 dB, while *Leaves Rustling* and *Muffled Conversation* were amplified by 30dB. As the stimuli used in this experiment were recordings of natural sounds, they often contained a spread of detail and intensity in a wide range of frequencies. The intensity of vibrotactile stimuli presentation using the Haptuator, however, was heavily dependent on the intensity of the bass frequencies, hence these five stimuli were adjusted to normalise intensity across stimuli in pilot testing. The reason why the bass frequencies of certain stimuli were increased, rather than simply raising the volume, was to avoid leakage of the higher frequency sound the actuator. One upside of using vibrotactile cues in social settings is they can experienced without significant noise pollution, and these stimuli were adjusted to adhere to that use case. Stimuli were cropped to a 10-second duration following findings from Experiment 1 that adaptation and sensation deadening occurred during the second half of longer 20-second stimuli.

3.3.3 Participants

20 participants (9 male, 8 female, 3 non-binary) were recruited using the same university, email and social media channels, with the same age and haptic perception requirements as in Experiment 1. Mean participant age was 27.2 ($\sigma = 5.71$).

3.3.4 Procedure

The same lab room and apparatus was used as in Experiment 1 and participants were paid £6 for their participation, which took approximately fourty minutes. Participants read an information sheet [B.2.1] before signing a consent form [B.2.2] to proceed with the experiment.

This experiment featured two tasks. In the first, participants experienced each of the eight stimuli three times in total, presented in a randomised order. After each stimulus, the participant recorded their arousal and valence on 7-point Likert scales identical to those used in Experiment 1, with responses encoded to a range of -3 to 3. They then chose which sensation the stimulus they just experienced reminded them of the most from a selection of thirteen options, including the eight stimuli present in the set (see Figure 3.9. If they felt none of the options were reminiscent they could indicate 'None' or 'Other' and write a different sensation.

In the second task, participants again experienced the stimuli set in the same randomised manner and reported arousal and valence responses to each one. In this task, however, the identity of each stimulus was given to the participant before they submitted their rating and they

[5] MP3Gain. http://mp3gain.sourceforge.net/
[6] Audacity. https://www.audacityteam.org/about/

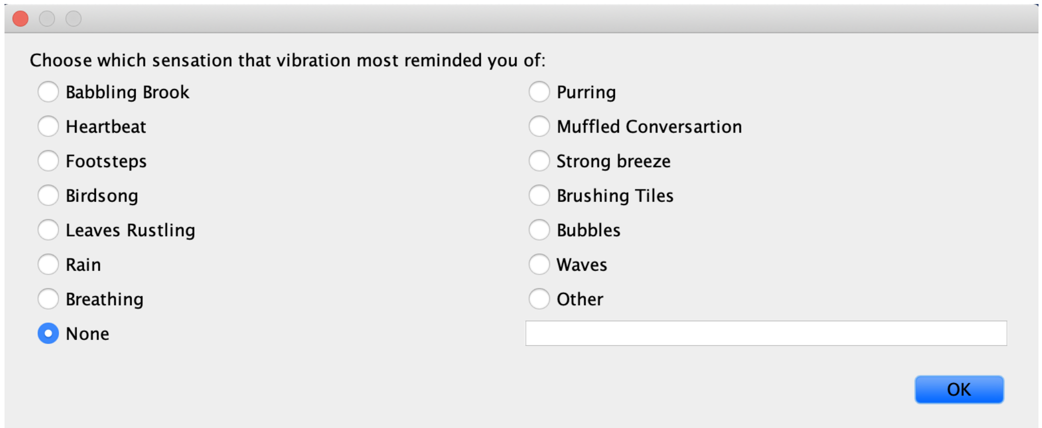


Figure 3.9: Panel displayed to participants during Experiment 2 - Task 1 after they have submitted valence and arousal ratings for a stimulus. Participants had to indicate which sensation that stimulus reminded them of, if any.

did not have to try and identify it. Identified stimuli were presented in a separate task after the unidentified stimuli to prevent participants being given a stimulus's identity and then using it to correctly identify it later on. Again, participants wore headphones playing brown noise during both tasks.

Following both tasks, participants took part in a semi-structured interview with four questions to establish if they found any particular stimuli resonant and if they noticed any difference between the identified and unidentified stimuli:

1. *Did you feel differently in Task 1 compared to Task 2? Followup: Did you notice any difference in how the stimuli felt?*

2. *During Task 2 were there any stimuli which were more resonant after being told what they were? Followup: were any stimuli still unrecognisable even after being labelled?*

3. *Did you have a stimulus you particularly enjoyed, did not enjoy, or stood out? Why?*

4. *Do you have any other comments or thoughts on the experiment and the sensations you experienced?*

These questions were designed to assess if participants felt stimuli identification had an impact on emotional response and if they felt emotional resonance with any stimuli, and if so gain insight as to why and how it affected their experience.

3.3.5 Results

Main Effects and Interactions Effects of Stimulus and Identification

As in Experiment 1, the Aligned Rank Transform was utilised prior to any parametric testing [7]. A pair of two-factor ANOVAs were performed: one searching for main and interactions effects of stimulus and identification on arousal, and the other searching for effects on valence.

Identification / Stimulus Main Effects on Valence	F	Df	P.Value
Identification	1.204	1	0.2735
Stimulus	8.950	7	**<0.0001**
Identification / Stimulus	0.523	7	0.8166
Identification / Stimulus Main Effects on Arousal	**F**	**Df**	**P.Value**
Identification	0.811	1	0.3686
Stimulus	12.86	7	**<0.0001**
Identification / Stimulus	2.099	7	**0.0437**

Table 3.5: Experiment 2 main effects of stimulus presented and stimulus labelling on arousal and valence. P values which indicated significant main effects and interactions effects are marked in bold.

Stimulus, i.e. which of the stimuli the participant experienced prior to each recorded emotional response, had a significant impact on both valence ($F = 8.94, df = 7, p < 0.05$) and arousal ($F = 12.86, df = 7, p < 0.05$) (see Table 3.5). Identification, i.e. whether the participant was given the identity of the stimuli they reported their emotional response, did not have a main effect on either valence or arousal. There was, however, an interaction effect between stimulus presented and identification on arousal ($F = 2.10, df = 7, p < 0.05$). To investigate this interaction, and determine the effects that specific stimuli in the set had on emotional response, *post hoc* testing was conducted.

Post Hoc Analysis

Single factor pairwise analysis with Tukey P value adjustment was conducted to estimate the difference in marginal means of emotional response between specific stimuli in the set. Calculating the significant contrasts between stimuli allowed observation of which stimuli accounted for the main effects on emotional response and if any specific stimulus was significantly more or less pleasant or arousing than others. Stimuli which, when contrasted with other cues had either significantly higher valence or lower arousal, would be more likely to serve induce a pleasant or calming sensation, the qualities desired for the planned social exposure intervention.

[7] The results of this experiment have been previously reported in a conference paper at ICMI 2020. In that paper both tasks were analysed separately, but in this thesis the tasks were analysed as one data set with their identification status operating as an independent variable. As such the results reported in this thesis are not identical to those reported in that paper. Substantial differences in results or conclusions drawn will be noted.

Stimulus	Mean Valence	Mean Arousal	Mean Accuracy
Babbling Brook	0.89	-0.87	10%
Slow Breathing	-0.28	0.35	5%
Underwater Bubbles	-0.13	1.05	15%
Heartbeat	0.95	0.19	93%
Leaves Rustling	0.50	0.41	7%
Muffled Conversation	0.27	0.56	10%
Cat Purring	0.83	0.47	27%
Crashing Waves	0.67	-0.02	15%

Table 3.6: Mean valence and arousal responses to the eight stimuli, and the mean identification accuracy of unidentified stimuli during Task 1.

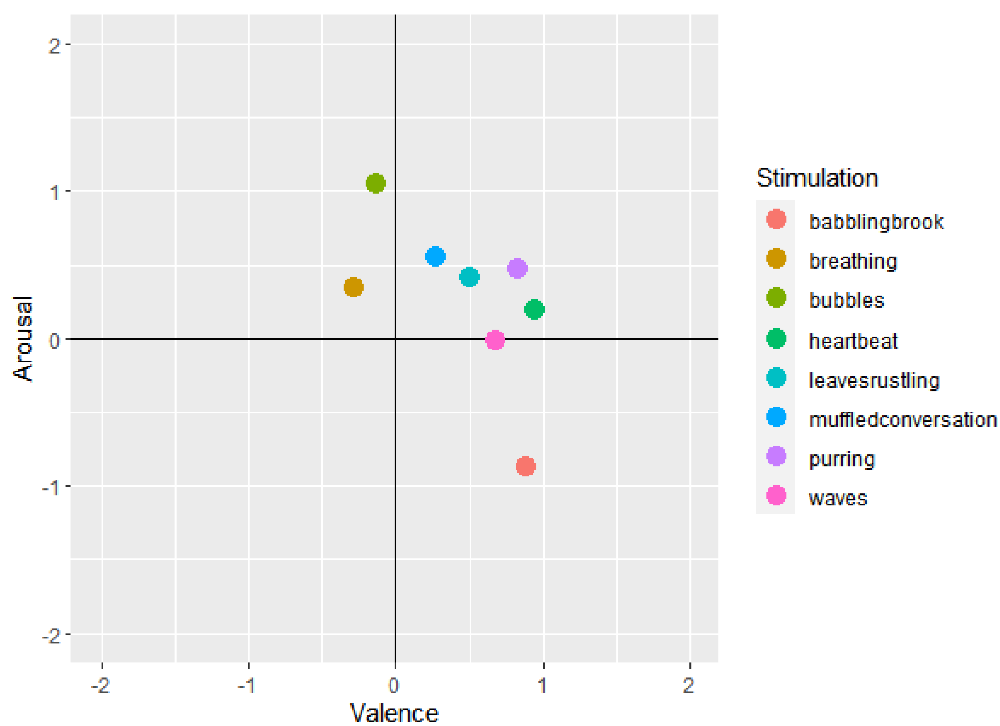


Figure 3.10: Valence - Arousal plot of each emotionally resonant stimulus. Valence and arousal were reported on a +3 to -3 Likert Scale, so it should be noted this plot is limited to a +2 to -2 range for clarity.

Valence Response Differences Between Stimuli

There was a significant difference ($p < 0.05$) between the valence responses to 10 stimuli comparison pairs from a total of 28 pairs (see Table 3.3.5). All eight stimuli appeared in at least one contrast. *Slow Breathing* contrasted with five other stimuli and was less pleasant than every other stimuli it significantly contrasted with. *Underwater Bubbles* significantly contrasted with four other stimuli and was also the less pleasant of each contrast. *Heartbeat* was significantly more pleasant than three other stimuli, including *Muffled Conversation* in addition to *slow Breathing* and *Underwater Bubbles*. *Cat Purring, Babbling Brook* and *Crashing Waves* each appeared in two significant contrasts, being also significantly more pleasant than *slow breathing* and *Underwater Bubbles*.

When considered alongside the mean valence responses for each stimulus (see Table 3.3.5), it can be observed that significant contrasts took place, as expected, primarily between stimuli with the most disparate averages. *Slow Breathing* and *Underwater Bubbles* were the only stimuli with average negative valence ratings and contrasted with stimuli with the highest ratings: *Cat Purring, Heartbeat and Babbling Brook*. These higher valence stimuli, however, only contrasted with one other stimuli between them.

Arousal Response Differences Between Stimuli

There was a significant difference ($p < 0.05$) between the arousal responses to ten stimuli comparison pairs from a total of twenty-eight pairs (see Table 3.3.5). The majority of contrasts featured *Babbling Brook* which had significantly lower arousal than every other stimuli it significantly contrasted with. *Underwater Bubbles* was present in the other three significant contrasts, being significantly more arousing than *Slow Breathing, Heartbeat* and *Crashing Waves*. These *post hoc* findings are well illustrated by the Valence - Arousal Plot (see Figiure 3.10). The majority of stimuli are grouped by a narrow mean arousal range of -0.02 to 0.56, with only *Underwater Bubbles* and *Babbling Brook* significantly above and below this group.

Interaction of Stimuli Identification

The interaction effect on arousal between stimulus presented and identification was investigated using the *art.con* function of ARTools with holm p value adjustment. This investigation, however, found no instances where emotional responses to a stimulus significantly changed based on whether the stimulus was identified for the participant or not.

A significant positive correlation was found between accuracy and valence ($cor = 0.161, p < 0.05$). There was, however, only one stimuli with more than 27% recognition accuracy, *Heartbeat* (see Figiure 3.13), which also had the highest average valence of 0.917 and so this correlation is heavily influenced by responses to just one stimuli. It is possible that the ease of recognition of this stimulus did positively contribute to its valence, but as an outlier no conclusions can be drawn.

Stimuli Valence Contrasts	Effect Size	Estimate	T.Ratio	P.Value
Babbling Brook - Slow Breathing	1.190	89.05	5.321	<0.0001
Babbling Brook - Underwater Bubbles	0.993	74.33	4.441	0.0003
Slow Breathing - Heartbeat	-1.288	-96.38	-5.759	<0.0001
Slow Breathing - Leaves Rustling	-0.755	-56.52	-3.378	0.0187
Slow Breathing - Cat Purring	-1.139	-85.28	-5.096	<0.0001
Slow Breathing - Crashing Waves	-0.927	-69.40	-4.147	0.0011
Underwater Bubbles - Heartbeat	-1.091	-81.65	-4.879	<0.0001
Underwater Bubbles - Cat Purring	-0.943	-70.55	-4.216	0.0009
Underwater Bubbles - Crashing Waves	-0.731	-54.67	-3.267	0.0265
Heartbeat - Muffled Conversation	0.718	53.75	3.210	0.0315

Table 3.7: The ten significant pairwise contrasts between stimuli found when estimating differences in marginal mean valence responses. Effect size reflects the standardised difference of means in valence between the first and second stimulus. Positive effect sizes indicate the first stimulus in the pair had higher valence responses and *vice versa*.

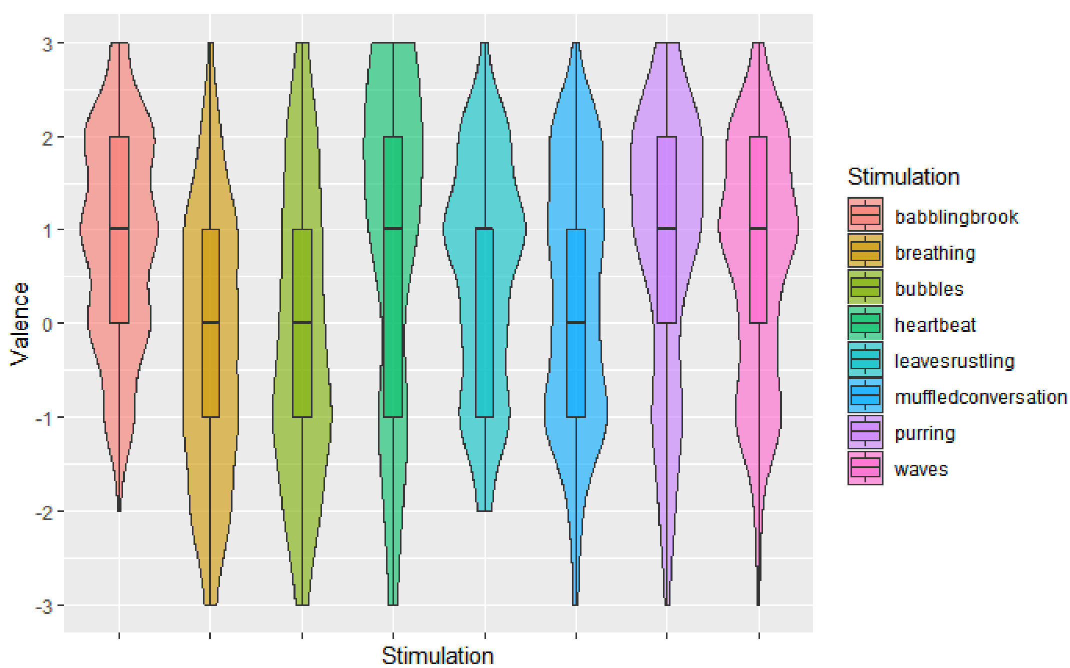


Figure 3.11: Violin plots showing distribution density and the median and interquartile valence responses to each stimulus in the set.

Stimuli Arousal Contrast	Effect Size	Estimate	T.Ratio	P.Value
Babbling Brook - Slow Breathing	-1.236	-86.42	-5.529	<0.0001
Babbling Brook - Underwater Bubbles	-1.981	-138.07	-8.770	<0.0001
Babbling Brook - Heartbeat	-1.020	-71.28	-4.560	0.0002
Babbling Brook - Leaves Rustling	-1.328	-92.85	-5.940	<0.0001
Babbling Brook - Muffled Conversation	-1.471	-102.83	-6.578	<0.0001
Babbling Brook - Cat Purring	-1.356	-94.78	-6.063	<0.0001
Babbling Brook - Crashing Waves	-0.887	-61.98	-3.965	0.0023
Slow Breathing - Underwater Bubbles	-0.725	-50.65	-3.240	0.0287
Underwater Bubbles - Heartbeat	0.941	65.80	4.210	0.0009
Underwater Bubbles - Crashing Waves	1.074	75.10	4.805	0.0001

Table 3.8: The ten significant pairwise contrasts between stimuli found when estimating differences in marginal mean arousal responses. Effect size reflects the standardised difference of means in arousal between the first and second stimulus. Positive effect sizes indicate the first stimulus in the pair had higher arousal responses and *vice versa*.

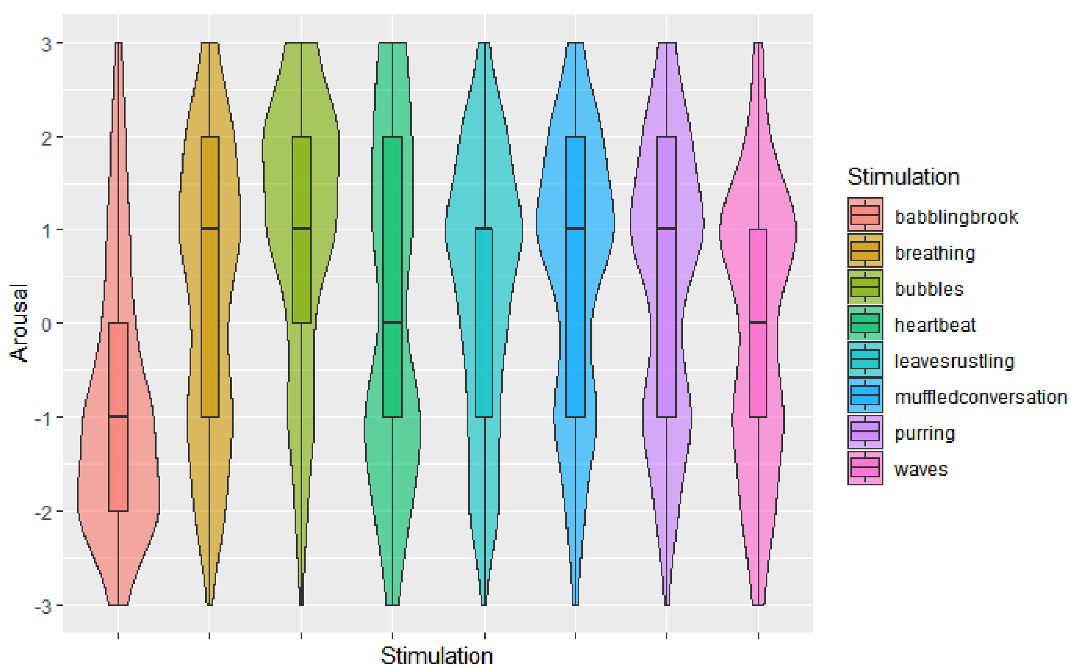


Figure 3.12: Violin plots showing distribution density and the median and interquartile arousal responses to each stimulus in the set.

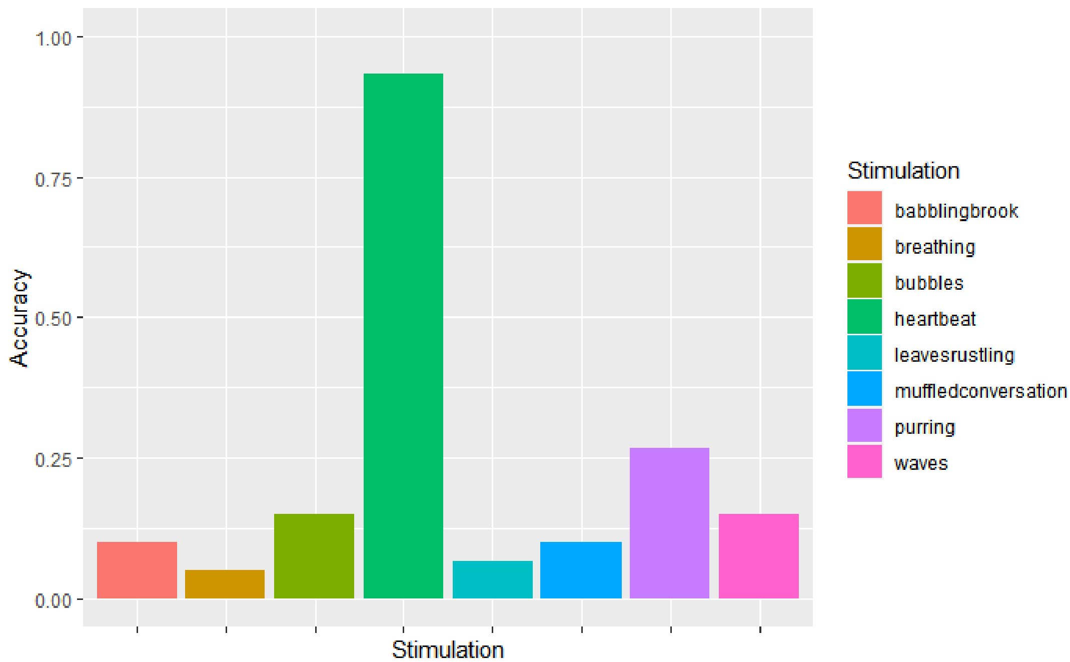


Figure 3.13: Bar chart comparing how accurately participants could identify emotionally resonant stimuli in Experiment 2, Task 1.

Qualitative Feedback

Analysing emotional responses to emotionally resonant stimuli when: (1) participants may or may not find some emotionally resonant and (2) participants may have variable emotional associations with original sensations the stimuli evoke, presents a complex challenge that cannot be captured solely with quantitative data. Understanding, via qualitative data collection, the rationale behind why participants reported certain emotional responses was crucial context in interpreting quantitative results. Participants expressed a wide variety of views in response to the three post-experiment interview questions and these statements were grouped by topic and sentiment.

Question 1: Did you feel differently in Task 1 compared to Task 2? Followup: Did you notice any difference in how the stimuli felt?

This first question explored if participants felt that stimuli being identified for them, versus having to try and recognise it themselves, impacted their experience. Overall, eight participants indicated that they felt it changed their perception in some way and eight others felt no difference, but details varied between responses. Six commented that when stimuli were labelled they found it easier to make positive associations: "things you thought were not that pleasant, when you hear they are like breaking waves, or whatever, they feel more pleasant", "When you realise what it is you can kinda visualise it in your mind and it changes your perception of it". Six people noted that when they had the identity of a stimulus they correctly recognised during Task 1 confirmed in Task 2 they felt satisfied, but five others commented that when they recognised a stimuli and found out they were wrong, they felt the stimulus became less pleasant or they suffered irritation that negative impacted their emotional response. Four people commented that many of the stimuli felt similar to each other, although three of those noted that the *Heartbeat* was particularly distinctive. Several participants made note of a specific stimulus they found especially resonant or especially dissonant, a topic directly addressed in the second and third questions.

Question 2: During Task 2 were there any stimuli which were more resonant after being told what they were? Followup: were any stimuli still unrecognisable even after being labelled?

The second question observed notable examples of when participants found stimuli more or less resonant once they could compare their perception to the stimulus's identity. Some stimuli were commonly mentioned, while others only rarely (see Table 3.9).

Stimulus	Resonant	Dissonant
Babbling Brook	3	0
Slow Breathing	1	4
Underwater Bubbles	8	0
Heartbeat	11	0
Rustling Leaves	4	4
Muffled Conversation	1	2
Cat Purring	10	0
Crashing Waves	2	3

Table 3.9: Table showing how often, when asked to name identified stimuli participants felt were resonant or dissonant, each of the eight stimuli was mentioned during semi-structured interviews following Experiment 2.

Heartbeat (mentioned 11 times), *Cat Purring* (10), *Underwater Bubbles* (8) and *Rustling Leaves* (8) were the most commonly mentioned stimuli. The first three were unanimously found resonant by those who made note of them, but only half of those who mentioned *Rustling Leaves* found it a resonant stimulus. All but one of the five participants who mentioned *Slow Breathing* found it dissonant. Two participants said they found stimuli like *Slow Breathing* dissonant as, when presented via vibration, they felt proportionally more intense then they would when experienced in a real setting. At least one participant found each stimulus emotionally resonant but there was no stimulus cited as resonant by more than eleven participants.

Question 3: Did you have a stimulus you particularly enjoyed, did not enjoy, or stood out? Why?

The third question observed which stimuli participants felt the strongest preference for, or had the strongest reaction to, and explore why they felt they had that response. Each stimuli was described as spotlighted by at least one participant (see Table 3.10).

Stimulus	Enjoyed	Disliked
Babbling Brook	1	1
Slow Breathing	1	6
Underwater Bubbles	4	3
Heartbeat	12	4
Rustling Leaves	1	0
Muffled Conversation	2	0
Cat Purring	9	2
Crashing Waves	4	1

Table 3.10: Table showing how often, when asked which stimuli stood out the most to them as one they enjoyed or disliked, each of the eight stimuli was mentioned during semi-structured interviews following Experiment 2.

Heartbeat was raised by 16 people. Twelve participants specifically expressed preference for it with accompanying comments like "familiar", "natural", "reminded me of my baby's heartbeat", "the regular rhythm was relaxing" and "enjoyable because I could recognise it". Four expressed dislike, citing negative emotional associations: "I hated the heartbeat, I imagined holding a bloody heart in my hand", "Reminded me of a hospital" and "Reminded me of when I am stressed and I can feel my heartbeat really clearly". *Cat Purring* was mentioned by eleven participants and enjoyed by nine of them. Several were cat owners or liked cats and found the stimulus pleasantly resonant: "I'm a cat lover and when I feel purring I think 'very nice'", "I have a cat at home so it was just like 'yes'", "I have a cat and cat purring is great". One participant noted a dissonance between feeling the stimulus and a positive bias towards the label, however: "I like cats, but I didn't like this feeling. When I saw it was purring I wanted to rate it higher, but made myself not do so". *Underwater Bubbles* and *Slow Breathing* were both mentioned seven times. Bubbles received a mixed response; some felt it was somewhat resonant to the original sensation with one participant saying it was "a bit like a kettle boiling", but two others noted it felt too intense. *Slow Breathing* was disliked by all but one of those who mentioned it, but was not necessarily dissonant, being described as "unhealthy" and feeling like "phlegm-y breathing". *Babbling Brook* was only mentioned twice but showcased an interesting example of a specific emotional association can shape emotional response, as one participant said the name 'Babbling Brook' provoked an unpleasant response as "I associate them with witches. I think back to Shakespearean things", referencing the three witches from Shakespeare's *Macbeth*. *Crashing Waves, Leaves Rustling* and *Muffled Conversation* were majoritively not mentioned and received no specific comments about why they were or were not preferred.

No additional comments about experiencing the stimuli were made during the fourth question. When considering responses to all three questions there were many prominent examples of participants directly reporting emotional resonance and relating this to their subsequent emotional response to certain stimuli. At the end of the study one person commented: "I liked them because I enjoy them in the real world as well so when I felt the vibration it gave me the same kind of feeling". Each participant mentioned at least one stimulus (and two on average) that they found resonant and pleasant. It is clear that each stimulus is only resonant for a variable subset of participants and, even among those who do find a stimulus emotionally resonant, the resulting emotional association will not necessarily be pleasant or positive.

3.3.6 Discussion

Experiment 2 showed the emotional responses to a novel set of emotionally resonant vibrotactile stimuli with the explicit aim of producing calmer and more pleasant responses than prior abstract waveforms. It also explored whether these stimuli were recognisable without identification and if being identified or recognised altered emotional response.

Hypothesis 1 Discussion

The majority of stimuli were grouped narrowly in the top-right quadrants of the Circumplex Model (see Figuire 3.10) indicating stimuli were overall somewhat pleasant and slightly alerting. The first hypothesis postulated that these emotionally resonant stimuli would exhibit a wider range of valence responses than the abstract stimuli used in Experiment 1 and prior work. When examining mean valence responses across the stimuli set , this did not bear out: in both experiments the mean valence responses to all stimuli were within -0.5 to 1 on a -3 to 3 scale. Participants did, however, leave a wider distribution of individual ratings on emotionally resonant stimuli than abstract stimuli (see Table 3.11), but this did not result in meaningfully different mean responses.

Stimuli Set	Valence Standard Deviation	Arousal Standard Deviation
Abstract Stimuli	1.199	1.218
Emotionally Resonant Stimuli	1.381	1.478

Table 3.11: Table showing the mean standard deviation of valence and arousal responses to both the abstract stimuli set from Experiment 1 and the emotionally resonant stimuli set from Experiment 2.

When considering this alongside the qualitative feedback participants gave, this is unsurprising. Participants indicated that their emotional response to an emotionally resonant stimulus was affected by whether they had a of positive or negative emotional association they had with the sensation being evoked. Additionally, the average emotional responses to each stimulus were drawn both from participants who found the stimulus resonant and those who felt no resonance or emotional association. It is to be expected, then, that these stimuli would exhibit a wider distribution of emotional response ratings, but not necessarily a wider range of mean ratings, as different stimuli were resonant for different participants and elicited different emotional responses. This highlighted the importance of contextualising quantitative emotional response data with qualitative feedback when observing the emotional responses to emotionally resonant vibrotactile stimuli and was an early indication of the need to prioritise personalisation when leveraging emotionally resonant stimuli as a social anxiety intervention later in the thesis.

Hypothesis 2 Discussion

Hypothesis 2 expected that participants would find stimuli emotionally resonant if they had an emotional association with the sensation the stimuli evoked. This hypothesis was supported by qualitative results. In many instances, participants found stimuli pleasant and emotionally resonant with their prior experiences and every participant found at least one stimulus emotionally resonant. The emotional associations made by participants varied, from distinct personal experiences ("I have a cat and cat purring is great", "Felt like a phlegm-y breathing") to more abstract associations ("Creepy and unsettling", "Felt natural") to imagined imagery ("I imagining holding a bloody heart in my hand"). It is clear, however, that this cannot be considered a consistent effect. There were several examples of participants finding a stimulus dissonant when they had an expectation based on experience with the evoked sensation (Regarding *Crashing Waves*: "I thought I was at the beach but I still didn't make this association."). Additionally, while stimuli like *Heartbeat, Cat Purring* and *Crashing Waves* received significant discussion, others like *Rustling Leaves* and *Muffled Conversation* made little to no impression on most participants and were barely mentioned. More generally several participants highlighted that they felt positively toward stimuli they could form an emotional association with and *vice versa*; ("I didn't enjoy vibrations that I couldn't guess or associate with."). Vibrotactile stimuli can be emotionally resonant and can elicit emotional responses that participants associate with the sensation they evoke, but not all participants will find a stimulus effective, even if they do possess an emotional association with the original sensation.

Hypothesis 3 Discussion

It was expected by Hypothesis 3 that stimuli which achieved a high level of recognition or that were identified for participants would achieve higher valence ratings and more emotional resonance. This was not well supported by the quantitative data, however, as there was no significant difference in valence responses between unidentified and identified stimuli. While there was a positive correlation between valence and accuracy, the highest valence stimulus (*Heartbeat*) was also an outlier when compared to the rest of the stimuli with <27% recognition accuracy, making it difficult to draw wider conclusions based on this correlation. During qualitative feedback two participants stated that they felt more positively toward a stimulus when they recognised it or had their recognition confirmed in Task 2 ("I was pleased when I could correctly identify stimuli", "When I made the connection it felt good"). Several mentioned that during Task 2 when stimuli were identified they found stimuli less pleasant when they discovered that they had incorrectly recognised a stimulus as a different sensation. This could have caused some stimuli to be rated more negatively during Task 2, while others reported that they found more stimuli pleasant in Task 2 when given identification to help form an association. Generally, there was no strong trend describing how the presence of stimulus identification, or how recognisable a stimulus was, affected overall emotional response.

Experiment 2 directly addressed Research Question 1: *Can single-actuator vibrotactile stimuli be emotionally resonant of real-world sensations?* Significant evidence was found to suggest that these stimuli could be emotionally resonant, as participants reported feeling emotional resonance with an average of two stimuli each and many made explicit mention of emotional associations they made between a stimulus and the sensation it originated from. Additionally, emotional response ratings showed a wider deviation than abstract stimuli, indicating that these stimuli could provoke more varied responses from individuals. It was also clear that individual differences play a significant role in the efficacy of these emotionally resonant stimuli, as whether a stimulus was found to be emotionally resonant varied from participant to participant, as did the emotional association and response they had when experiencing it.

This experiment provided a promising foundation for further investigation of this novel stimuli category, as well as some limitations to address. Observation of emotional resonance relied solely on qualitative discussion of the most notable stimuli, resulting in far less data associated with less distinctive sensations. As this experiment assessed recognition, participants were not given the opportunity to experience the stimuli set before rating. No direct statistical comparison could be made between abstract and emotionally resonant stimuli, as only the latter was studied in this experiment. Experiment 3 addressed these limitations, while also gathering emotional responses and qualitative data on a larger selection of emotionally resonant stimuli candidates, and investigated the impact of a thermotactile component on emotional resonance and response.

3.4 Experiment 3: Emotionally Resonant Vibrotactile and Thermotactile Cues

Experiment 3 built on the emotionally resonant vibrotactile research conducted in Experiment 2 by addressing its limitations and expanding the range of stimuli tested. The larger vibrotactile stimuli set contained 15 emotionally resonant and nine abstract stimuli, and emotional resonance was self-reported following each stimulus presentation, as well as valence and arousal. In addition, this experiment aimed to improve understanding of emotionally resonant stimuli by presenting vibrotactile cues alongside neutral, cold and warm thermotactile stimuli. There were several reasons to investigate combining emotionally resonant vibrations with thermal cues. In prior work, thermotactile stimuli have been combined with vibrotactile stimuli to widen and influence their valence range [230] and thus it was valuable to observe the effect they had on emotionally resonant stimuli. In addition, temperature has previously been used to increase the emotional resonance of images [156] and warmth in particularly has an inherent element of social closeness [227] that might impact stimuli which evoke human experiences. Finally, during Survey 2, which was conducted prior to Experiment 3, *Warm* sensations were among the most prominent participant preferences when asked to choose sensations they felt would be calming in different social scenarios. This all motivated evaluating thermal cues in this emotional resonance context. This experiment would provide a broader and deeper understanding of emotionally resonant vibrotactile stimuli and inform which selection of stimuli should be offered to participants when implementing the social anxiety intervention in Chapter 5.

3.4.1 Methodology

This was a within-subjects experiment designed to observe emotional responses to both abstract and emotionally resonant vibrotactile stimuli presented at three temperature levels. The experiment had two independent variables: stimulus (which vibrotactile stimuli listed on Table 3.12 was presented) and temperature (warm, neutral, cold). Details on the stimuli and temperature levels used can be found in Section 3.4.2. In order to present both vibrotactile and thermotactile feedback simultaneously a new apparatus set-up was used (see Section 3.4.3).

Three dependent variables were measured: self-reported valence, self-reported arousal and self-reported resonance (for which participants rated how resonant each emotionally resonant stimulus was to the original sensation). Measuring resonance allowed observation of perceived emotional resonance for each stimulus, rather just inferring which were more or less resonant by often they were mentioned in qualitative feedback, as in Experiment 2. Whether any stimulus was statistically significantly more resonant than others could now be observed, as could any correlation between resonance and emotional response. It was speculated that certain emotionally resonant stimuli would be associated with their warm or cold thermal cues - for example *Cat Purring* would be more resonant if presented with warmth, while *Babbling Brook* would be more resonant when presented with cold - and that presenting these temperatures would thus improve the emotional resonance of these stimuli.

This experiment had four hypotheses centered around the impact that the new independent variable, temperature, would have on dependent variables, including resonance, as well as whether there was a statistical relationship between valence and emotional resonance and how emotionally resonant stimuli directly compared to abstract stimuli.

H1: Warm thermotactile cues will have a significant positive effect on valence and arousal;

H2: Participants will find emotionally resonant vibrotactile stimuli with an expected temperature more resonant or dissonant depending on the temperature;

H3: Stimulus resonance will positively correlate with stimulus valence and arousal;

H4: Emotionally resonant vibrotactile stimuli will receive a wider range of emotional responses and qualitative feedback than abstract vibrotactile stimuli.

Hypothesis 1 is founded on prior work measuring emotional responses to thermal cues [188] and combined vibrotactile and thermotactile stimuli [230] . Hypothesis 2 made a specific expectation about how thermal cues would interact with emotionally resonant vibrations. These hypotheses also directly address Research Question 2, *Can thermal cues be used to enhance the emotional resonance and affective range of vibrotactile stimuli?* If a thermal component succeeded in making emotionally resonant vibrotactile stimuli significantly more emotionally resonant and more pleasant to experience, it would motivate using it as part of social anxiety intervention, despite the practical drawbacks and loss of flexibility of thermal actuators. Measuring emotional resonance directly allowed Hypothesis 3 to be posited and, alongside more qualitative feedback, informed a better understanding of how a wider range emotionally resonant stimuli function.

3.4.2 Stimuli

A set of fifteen emotionally resonant stimuli were used in Experiment 3, with the aim to observe responses to a wider set of stimuli than Experiment 2. This experiment took place after Survey 2 (see Chapter 4, Section 4.3), which collected user suggestions for pleasant affective haptic sensations. Five stimuli which could be successfully presented via Haptuator were included in this experiment, embodying experience themes found in Survey 2: *Raindrops* , *Vacuum Cleaner* (Artificial - Artificial Sound), *Scratching* (Human Touch), *Brushing* (Human Touch), *Wind* (Natural - Wind) and *Car Engine* (Artificial - Machine Sound). Additionally, two more real-world sound phenomena which were found to be presentable via vibration were added: *Dog Growling* (Social/Natural - Animal Sound) and *Train Tracks* (Artificial - Artificial Sound) (the rhythmic sound of a train running over track segments, recorded from inside a carriage). Selection of which specific sound files from Freesound.org was once again based on manual pilot testing for presentation clarity and the total stimuli set can again be found in the Enlighten database.

Seven of the eight stimuli used in Experiment 2 were included, but *Rustling Leaves* was removed after no participants suggested it as a calming sensation in Survey 2 and it received neutral emotional ratings and scarce qualitative discussion in Experiment 2. Seven stimuli were assigned an 'expected temperature' to represent that the original phenomena were associated with warmth or cold (e.g. *Cat Purring* is associated with warmth). These stimuli would be given special consideration during analysis to see if they experienced an increase or decrease in resonance when presented at different temperatures. The full set of emotionally resonant stimuli and their expected temperature, if applicable, is listed in Table 3.12.

As before, all stimuli were sourced from Freesound.org[8] and, following feedback from aca-

[8]Freesound. https://freesound.org/help/about/

Emotionally Resonant Stimuli (with expected temperature if present)			
Cat Purring (Warm)	Raindrops (Cold)	Brushing	Slow Breathing
Small Stream (Cold)	Crashing Waves (Cold)	Dog Growling	Vacuum Cleaner
Car Engine (Warm)	Wind (Cold)	Muffled Conversation	Train Tracks
Heartbeat (Warm)	Underwater Bubbles	Scratching	

Table 3.12: Table listing all the full set of emotionally resonant vibrotactile stimuli presented in Experiment 3. Seven stimuli were assigned an expected temperature that may be associated with the original sensation.

demic reviewers when during the publication of Experiments 1 and 2 as a conference paper, the processing of files was adjusted. Rather than normalising volume and then boosting bass frequencies to achieve similar intensities, a 300Hz low-pass filter was applied to all stimuli to de-emphasise frequencies not well presented by the Haptuator. Following this, stimuli had their volume normalised to 89dB using MPGGain[9]. Three stimuli (*Cat Purring*, *Car Engine* and *Brushing*) were then reduced to 85dB following pilot feedback that they were disproportionately intense compared to the rest of the set. The nine abstract stimuli presented used identical combinations of amplitude and frequency to those used in Experiment 1 (see Table 3.13).

Parameter	**Values**
Amplitude	A1,A2,A3
Frequency	F1,F2,F3

	A1	**A2**	**A3**
F1: 90Hz	1.7g	3.3g	4.3g
F2: 200Hz	0.6g	1.0g	1.3g
F3: 300Hz	0.9g	1.2g	2.2g

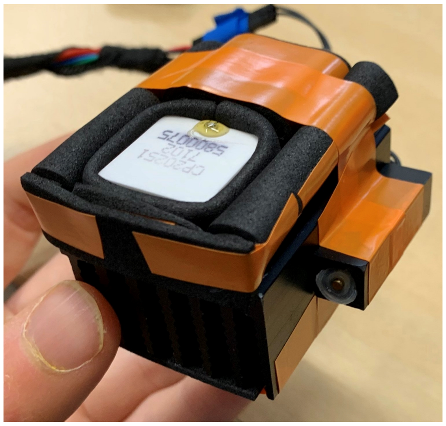
Table 3.13: Frequency and amplitude levels used to generate the nine abstract vibrotactile stimuli presented in Experiment 3. Amplitude levels were adjusted for different levels of frequency to normalise perceived intensity [230] (g = gravitational acceleration).

The duration of all stimuli was again set to 10 seconds. Stimuli were presented at three temperature levels throughout the experiment: a neutral level of 30°C, a colder level of 24°C and a warmer level of 34°C (reduced from 36°C following discomfort in pilot testing).

3.4.3 Apparatus

A new hand-rest was used for Experiment 3 to deliver simultaneous vibrotactile and thermotactile stimuli (see Figure 3.14). Thermal cues were conveyed using a Peltier thermoelectric heat element with an attached heat sink, a device used in numerous prior works [67, 189, 208, 230]. As this is a fully rigid component, the Haptuator Mk II was attached firmly to the body of the heat-sink with electric tape and effectively conveyed vibration throughout the body of the device. A foam cover was fashioned to fit around the heat element on top of the device, allowing participants to rest the heel of their palm upon the element and let their fingers drape around

[9]MP3Gain. http://mp3gain.sourceforge.net/



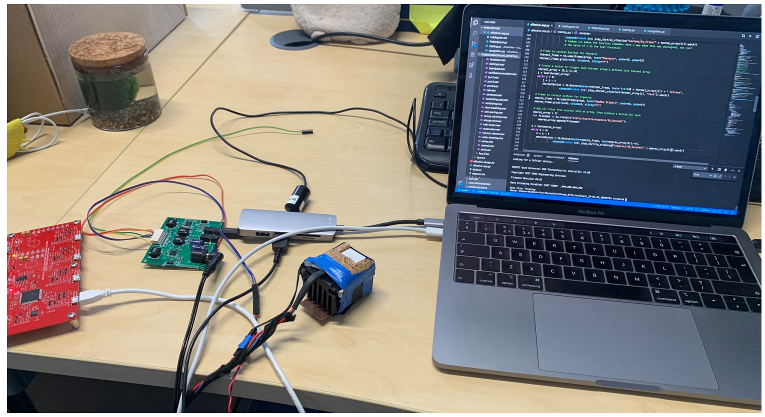


Figure 3.14: Experimental apparatus used in Experiment 3. A Haptuator Mark II was tightly bound to a heatsink and Peltier thermoelectric element to create an all-in-one handrest for delivering vibrotactile and thermotactile feedback. The Haptuator was controlled via a Haptu-Amp-Quad and the Peltier via a QUUTEC Quad Universal USB ThermoElectric Controller and a laptop computer.

the device comfortably. With their hand in this position participants could experience simultaneous thermal stimulation on their palm from the heating element and vibrotactile stimulation to their hand throughout the entire device. Underneath the device, a small circle of thin foam was placed to absorb the vibration which would otherwise be conveyed through the table by the rigid heat-sink and reduce noise. The Peltier was controlled by the laptop via a QUUTEC Quad Universal USB ThermoElectric Controller [A.3] and, as before, the Haptuator was controlled via the Haptu-Amp-Quad board. The laptop used was a 2018 13" 2.3GHz Core i5 MacBook Pro with its internal volume level set to 6.

3.4.4 Participants

20 participants (11 male, 8 female, 1 non-binary) were recruited using university, email and social media channels. As in Experiments 1 and 2, participants were required to be at least 18 years old and have full haptic perception in their hands.

3.4.5 Procedure

The experiment took place in a lab room with a table, chair, laptop computer and the haptic hand-rest. Participants were paid with a £10 Amazon voucher for their participation which took approximately 50 minutes. Participants read an information sheet [B.3.1] and signed a consent form [B.3.2] to proceed with the experiment.

The experiment was structured into three tasks (see Figure 3.15). Before data was collected, participants completed a training session corresponding to that task. The training took place in three rounds, mirroring the three task structure of the experiment to follow. Before Task 1

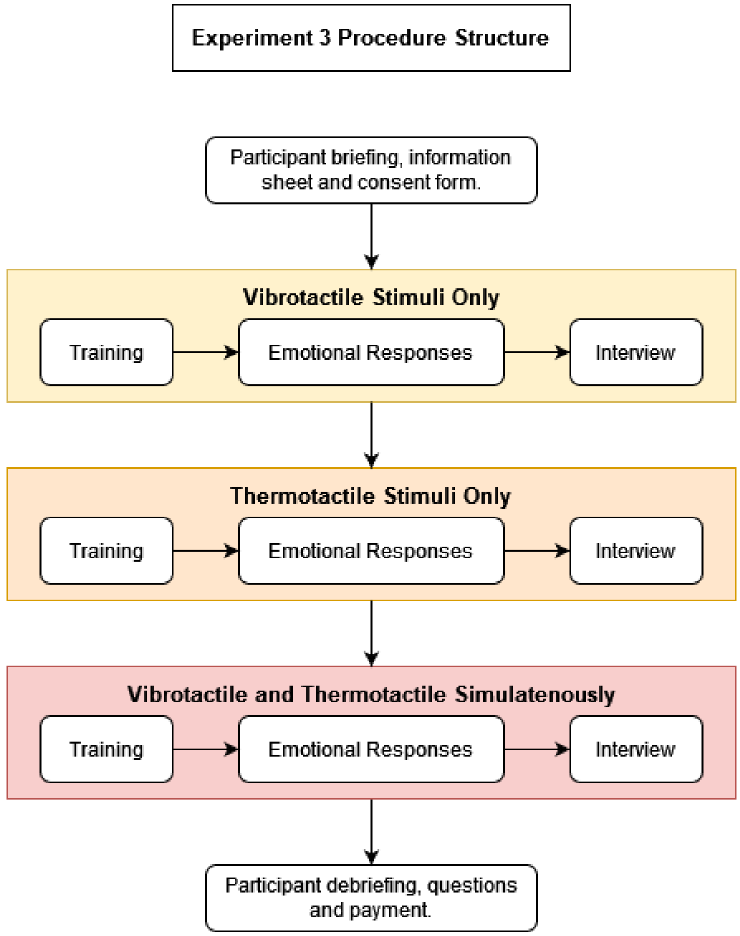


Figure 3.15: Diagram showing the procedure for Experiment 3. Participants underwent the same process in each task of training, followed by emotional responses to a randomised order of stimuli, followed by an interview question.

participants could freely choose to experience all of the vibrotactile stimuli at least once, using a GUI menu (see Figure 3.16). Then in Task 1 participants experienced all 24 vibrotactile stimuli (15 emotionally resonant vibrations and 9 abstract vibrations) presented at a neutral temperature of 30°C in a random order. The identity of each stimulus was given before emotional responses were recorded. After each stimulus, participants recorded their arousal and valence on 7-point Likert scales. Then, if the stimulus was an emotionally resonant vibration, a third 7-point Likert scale was presented and participants recorded how emotionally resonant they felt it was to the original sensation. All Likert scale responses were encoded on a range between -3 and 3, with low responses encoded on the negative half of the scale, high responses encoded on the positive half and neutral responses encoded as '0'. After completing the task, participants were recorded answering the following question: *Did any specific vibrations stand out to you during the experiment and why?*

Task 2 repeated this process but instead participants experienced four thermotactile levels, including the two levels used in Task 2 (34°C and 24°C) and two more granular levels, 28°C and 32°C. After completing the task participants were recorded answering the following question:

Which temperature level did you prefer and why?

In Task 3, participants experienced all twenty-four stimuli twice more, once at 24°C and once at 34°C, for a total of fourty-eight multimodal stimuli. After completing the task participants were recorded answering the following question: *Did you think the changes in temperature affected your perception of the vibrations?*

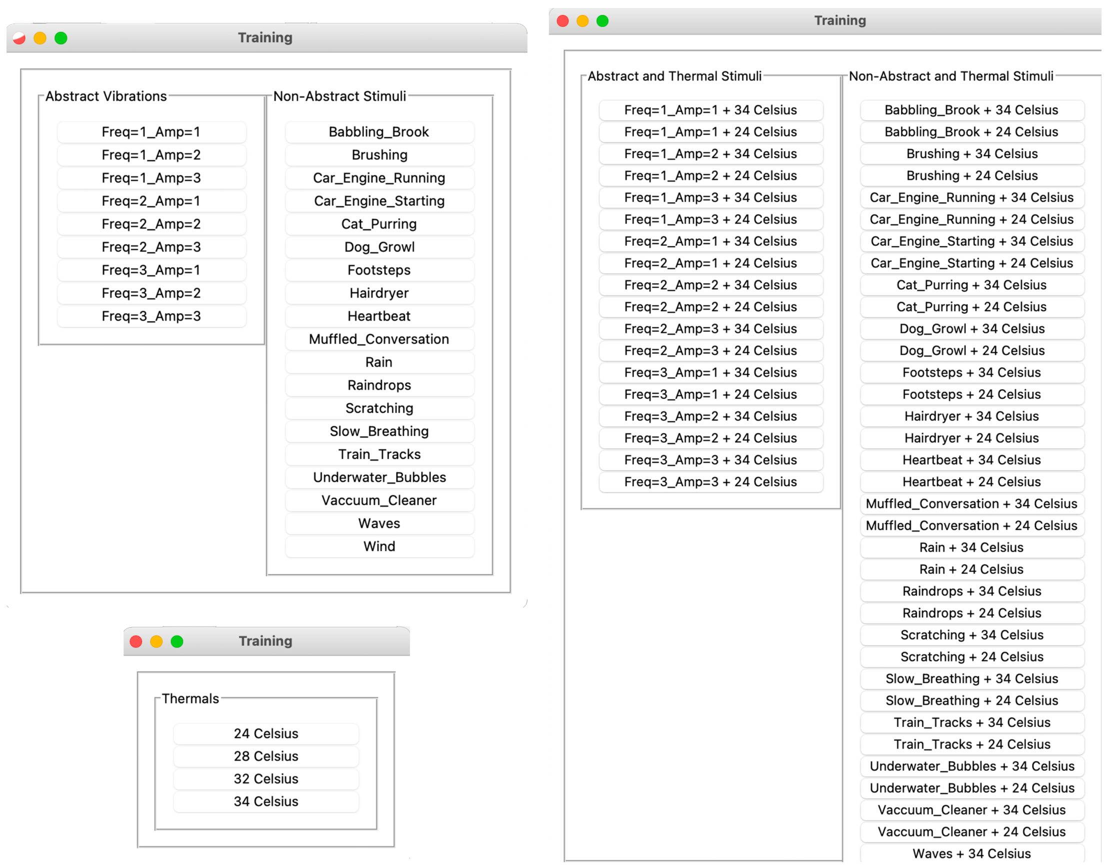


Figure 3.16: Three GUI windows displayed to the participant in sequence during Experiment 3 training. The first UI (top left) allowed participants to experience each vibration stimulus at least once before giving emotional responses. The second GUI (bottom right) allowed participants to experience all thermal cues. The third GUI (right) allowed participants to experience every combination of vibrotactile and thermotactile stimulus.

Training was added to this experiment to counter any learning effect caused by observing emotional responses to stimuli the first time they are perceived. Training was omitted from Experiment 2 as allowing participants to experience all identified stimuli would confound the ability to assess if participants could recognise emotionally resonant stimuli without additional information. Interview questions were positioned after their relevant tasks in this experiment, allowing participants to comment on each task immediately after experiencing them, rather than at the end of the session as in Experiments 1 and 2. During all three tasks participants wore headphones playing brown noise to mask noise pollution from the Haptuator.

3.4.6 Results

Discussion of the testing for main and interaction effects will be structured around the four hypotheses. The Aligned Ranked Transform was applied to Likert scale responses before parametric testing, as in Experiments 1 and 2.

Hypothesis 1 - Main Effects, Interaction Effects and *Post Hoc* Testing

H1 - Main and Interaction Effects

First Hypothesis 1, *Warm thermotactile cues will have a significant positive effect on valence and arousal*, was investigated. To comprehensively observe the effects of temperature on valence and arousal, six analyses of variance were conducted. Two single-factor ANOVAs were conducted observing the main effect of thermal cues on valence and arousal when presented in isolation in Task 2. Two three-factor ANOVAs observed the main and interaction effects of temperature, amplitude and frequency on the valence and arousal responses to abstract stimuli. Finally a pair of two-factor ANOVA observed the main and interaction effects of temperature level and which emotionally resonant stimulus was presented on valence and arousal (see Table 3.14).

When presented on their own thermal cues had no significant effect on valence ($F = 0.798, df = 3, p = 0.5002$). When presented alongside abstract stimuli, temperature again had no significant effect on valence. When presented alongside emotionally resonant stimuli, however, temperature had a main effect on valence ($F = 1.174, df = 2, p < 0.0001$).

The three ANOVAs searching for main and interaction effects of temperature on arousal (see Table 3.14) found more significant results. When presented in isolation during Task 2, a significant main effect by temperature on arousal was found ($F = 15.01, df = 3, p < 0.0001$). When presented alongside abstract stimuli, temperature had no main effect on arousal, but did have an interaction effect with amplitude ($F = 5.25, df = 4, p < 0.0004$). When presented alongside emotionally resonant stimuli, temperature had a main effect on arousal ($F = 5.21, df = 2, p < 0.0057$).

H1 - Post Hoc Testing

While thermal cues presented in isolation had no main effect on valence, they did on arousal, thus pairwise analysis of temperature's main effect on arousal when experienced in isolation during Task 2 was conducted. Four significant contrasts were found between levels out of six total (see Table 3.15). The warmest and coolest stimuli (34°C and 24°C) had significantly higher arousal than intermediate temperature levels, but not when compared to each other.

Following up on the main effect of temperature on valence and arousal when presented alongside emotionally resonant stimuli, *post hoc* single-factor pairwise analysis with Tukey P

Task 2 - Temperature on Valence	F	Df	P.Value
Temperature	0.798	3	0.5002
Task 2 - Temperature on Arousal	**F**	**Df**	**P.Value**
Temperature	15.01	3	**<0.0001**
Task 3 - Frequency / Amplitude / Temperature on Valence	**F**	**Df**	**P.Value**
Frequency	1.662	2	0.1908
Amplitude	0.045	2	0.9558
Temperature	0.272	2	0.7616
Frequency / Amplitude	0.218	4	0.9282
Frequency / Temperature	1.194	4	0.3123
Amplitude / Temperature	0.949	4	0.4354
Frequency / Amplitude / Temperature	0.623	8	0.7584
Task 3 - Frequency / Amplitude / Temperature on Arousal	**F**	**Df**	**P.Value**
Frequency	10.72	2	**<0.0001**
Amplitude	53.86	2	**<0.0001**
Temperature	2.569	2	0.0776
Frequency / Amplitude	3.505	4	**0.0078**
Frequency / Temperature	2.099	4	0.0797
Amplitude / Temperature	5.248	4	**0.0004**
Frequency / Amplitude / Temperature	1.156	8	0.3244
Task 3 - Emotionally Resonant Stimulus / Temperature on Valence	**F**	**Df**	**P.Value**
Stimulus	4.418	14	**<0.0001**
Temperature	10.43	2	**<0.0001**
Stimulus / Temperature	1.174	28	0.2450
Task 3 - Emotionally Resonant Stimulus / Temperature on Arousal	**F**	**Df**	**P.Value**
Stimulus	10.98	14	**<0.0001**
Temperature	5.206	2	**0.0057**
Stimulus / Temperature	0.913	28	0.5966

Table 3.14: Main and interaction effects of temperature and other relevant independent variables on participant valence and arousal when presented in isolation (Task 2) and alongside abstract vibrations (Task 3) and emotionally resonant vibrotactile stimuli (Task 3). P values which indicate significant main or interaction effects are bold.

T2 - Temperature Arousal Cons	Effect Size	Estimate	T.Ratio	P.Value
24°C - 28°C	1.047	17.55	3.311	0.0085
24°C - 32°C	1.565	26.23	4.948	<0.0001
28°C - 34°C	-1.320	-22.12	-4.174	0.0006
32°C - 34°C	-1.838	-30.80	-5.811	<0.0001
T3 - ER Temperature Valence Cons	**Effect Size**	**Estimate**	**T.Ratio**	**P.Value**
24°C - 30°C	-0.3580	-86.7	-4.385	<0.0001
24°C - 34°C	-0.2694	-65.2	-3.299	0.0029
T3 - ER Temperature Arousal Cons	**Effect Size**	**Estimate**	**T.Ratio**	**P.Value**
30°C - 34°C	-0.262	-59.7	-3.211	<0.0039
AB - Amplitude / Temperature Arousal Cons		**Estimate**	**T.Ratio**	**P.Value**
A1 / 24°C - A3 / 24°C		-90.36	-4.399	0.0004
A1 / 24°C - A3 / 30°C		-108.58	-5.286	<0.0001
A1 / 24°C - A3 / 34°C		-67.01	-3.262	0.0248
A1 / 30°C - A2 / 24°C		-78.36	-3.815	0.0037
A1 / 30°C - A2 / 30°C		-85.12	-4.144	0.0010
A1 / 30°C - A2 / 34°C		-89.65	-4.365	0.0004
A1 / 30°C - A3 / 24°C		-146.36	-7.125	<0.0001
A1 / 30°C - A3 / 30°C		-164.58	-8.013	<0.0001
A1 / 30°C - A3 / 34°C		-123.01	-5.989	<0.0001
A1 / 34°C - A2 / 24°C		-65.33	-3.181	0.0312
A1 / 34°C - A3 / 24°C		-122.04	-5.941	<0.0001
A1 / 34°C - A3 / 30°C		-140.27	-6.829	<0.0001
A1 / 34°C - A3 / 34°C		-98.69	-4.805	0.0001
A2 / 24°C - A3 / 24°C		-68.00	-3.311	0.0220
A2 / 24°C - A3 / 30°C		-86.22	-4.198	0.0009
A2 / 30°C - A3 / 30°C		-79.46	-3.868	0.0031
A2 / 34°C - A3 / 34°C		-74.93	-3.648	0.0067

Table 3.15: Significant contrasts of valence and arousal between temperature levels found by pairwise *post hoc* analysis. T2 (Task 2) contrasts resulted from temperature presentation in isolation. T3 contrasts resulted from temperature presented alongside emotionally resonant vibrations. AB contrasts resulted from temperature presented alongside abstract stimuli during Task 3.

Task 3 - Temperature / Stimuli Resonance Cons	Effect Size	Estimate	T.Ratio	P.Value
Heartbeat 24°C - 30°C	-1.2414	-13.45	-3.926	0.0010
Heartbeat 24°C - 34°C	-1.3198	-14.30	-4.174	0.0005
Small Stream 24°C - 34°C	1.1680	11.28	3.692	0.0020

Table 3.16: Table showing the three significant pairwise contrasts between fixed emotionally resonant stimuli presented at different temperature levels, from a total of fourty-five contrasts when estimating differences in marginal mean emotional resonance responses within a -3 to 3 range. Alpha set to 0.0033 with Bonferroni Correction.

	F1A1	F1A2	F1A3	F2A1	F2A2	F2A3	F3A1	F3A2	F3A3
Valence	0.58	0.48	0.53	0.52	0.33	0.43	0.35	0.33	0.28
Arousal	0.20	1.07	1.62	0.67	1.12	1.45	1.00	1.22	1.92

Table 3.17: Mean valence and arousal responses for abstract stimuli, averaged across Task 1 and Task 3. Valence and arousal responses given on a 3 to -3 scale, averaged across all temperature levels. F1, F2 and F3 represent 90Hz, 200Hz and 300Hz. and A1, A2 and A3 represent increasing amplitude levels calibrated dependent on frequency (See Table 3.13 for breakdown of stimuli frequency and amplitude levels).

	Breathing	Brushing	Bubbles	Car Engine	Cat Purr	Conversation	Dog Growl	Heartbeat
Valence	0.03	0.30	0.50	0.61	1.20	0.35	0.03	0.32
Arousal	-0.95	-0.57	0.15	0.23	0.25	0.38	0.38	1.37
Resonance	-0.40	-0.60	0.63	0.75	1.42	-1.48	-0.35	2.23
	Raindrops	Scratching	Stream	Train Tracks	Vacuum	Wave	Wind	
Valence	0.57	0.03	0.65	0.42	0.37	0.75	0.33	
Arousal	0.3	0.2	-0.28	0.38	-0.03	-0.12	-0.28	
Resonance	0.23	-0.55	0.3	0.12	-0.21	-0.10	-0.45	

Table 3.18: Mean valence, arousal and resonance responses to all emotionally resonant stimuli presented in Experiment 3, averaged across all temperature levels.

Emo. Res. Stimuli Valence Contrasts		Effect Size	Estimate	T.Ratio	P.Value
Breathing -	Cat Purring	-1.029	-244.37	-5.636	<0.0001
Brushing -	Cat Purring	-0.7858	-186.61	-4.304	0.0018
Cat Purring -	Muffled Conversation	0.8024	190.55	4.395	0.0012
Cat Purring -	Dog Growling	1.0753	255.37	5.890	<0.0001
Cat Purring -	Heartbeat	0.7366	174.93	4.035	0.0053
Cat Purring -	Scratching	0.9560	227.03	5.236	<0.0001
Cat Purring -	Train Tracks	0.6837	162.37	3.745	0.0158
Cat Purring -	Vacuum Cleaner	0.7545	179.18	4.133	0.0036
Cat Purring -	Wind	0.7169	170.24	3.926	0.0081
Dog Growling -	Waves	-0.6519	-154.81	-3.571	0.0289

Table 3.19: Table showing the ten significant pairwise contrasts between emotionally resonant, from a total of 105 contrasts when estimating differences in marginal mean valence responses within a -3 to 3 range.

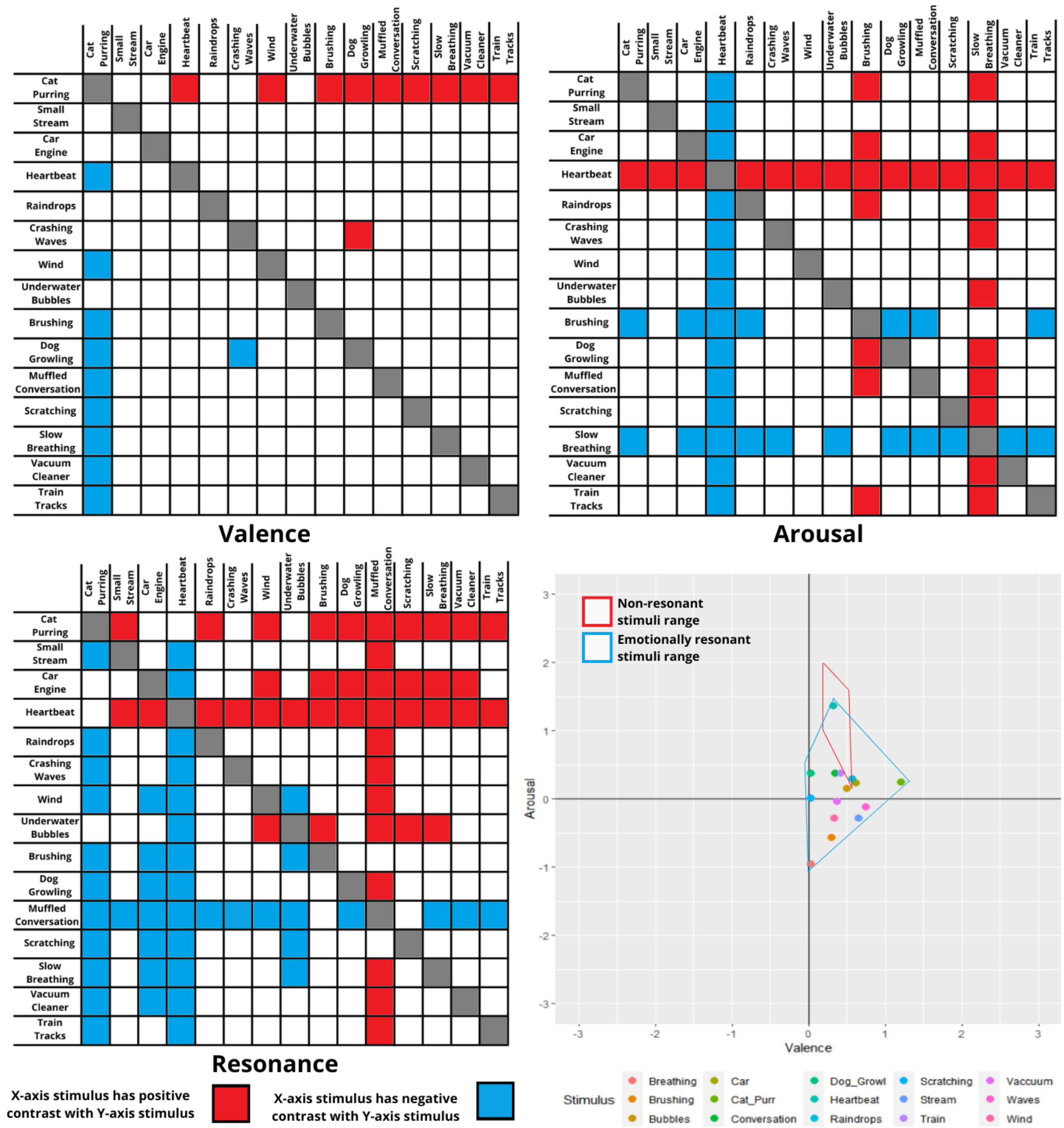


Figure 3.17: Figure showing three matrices displaying the significant contrasts of valence, arousal and emotional resonance between emotionally resonant stimuli and one valence-arousal plot of each stimulus' average affective response. Red squares indicate that the stimuli on the x-axis had a higher value of the associated variable than the stimuli on the y-axis, blue squares indicate the opposite. The bottom right graph shows a valence/arousal plot of the emotionally resonant stimuli, averaged across temperature levels. The blue lined area indicates the approximate affective range of emotionally resonant stimuli, the red lined area indicates the range of abstract stimuli not plotted to the graph (see Table 3.13)

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Emo. Res. Stimuli Arousal Contrasts		Effect Size	Estimate	T.Ratio	P.Value
Slow Breathing -	Underwater Bubbles	-0.8820	-188.83	-4.831	0.0002
Slow Breathing -	Car Engine	-0.9735	-208.42	-5.332	<0.0001
Slow Breathing -	Cat Purring	-1.0129	-216.88	-5.548	<0.0001
Slow Breathing -	Muffled Conversation	-1.0245	-219.36	-5.612	<0.0001
Slow Breathing -	Dog Growling	-1.0939	-234.22	-5.992	<0.0001
Slow Breathing -	Heartbeat	-1.8712	-400.65	-10.25	<0.0001
Slow Breathing -	Raindrops	-1.1555	-247.40	-6.329	<0.0001
Slow Breathing -	Scratching	-0.8871	-189.92	-4.859	0.0001
Slow Breathing -	Train Tracks	-1.1206	-239.92	-6.138	<0.0001
Slow Breathing -	Vacuum Cleaner	-0.7362	-157.62	-4.032	0.0053
Slow Breathing -	Crashing Waves	-0.6277	-134.40	-3.438	0.0445
Brushing -	Car Engine	-0.6449	-138.08	-3.532	0.0328
Brushing -	Cat Purring	-0.6844	-146.54	-3.749	0.0156
Brushing -	Muffled Conversation	-0.6960	-149.02	-3.812	0.0124
Brushing -	Dog Growling	-0.7654	-163.87	-4.192	0.0028
Brushing -	Heartbeat	-1.5427	-330.31	-8.450	<0.0001
Brushing -	Raindrops	-0.8270	-177.06	-4.530	0.0007
Brushing -	Train Tracks	-0.7921	-169.58	-4.338	0.0015
Underwater Bubbles -	Heartbeat	-0.9893	-211.82	-5.419	<0.0001
Car Engine -	Heartbeat	-0.8978	-192.22	-4.918	0.0001
Cat Purring -	Heartbeat	-0.8583	-183.77	-4.701	0.0003
Muffled Conversation -	Heartbeat	-0.8467	-181.29	-4.638	0.0004
Dog Growling -	Heartbeat	-0.7773	-166.43	-4.258	0.0021
Heartbeat -	Raindrops	0.7158	153.25	3.920	0.0082
Heartbeat -	Scratching	0.9842	210.72	5.391	<0.0001
Heartbeat -	Small Stream	1.3065	279.72	7.156	<0.0001
Heartbeat -	Train Tracks	0.7507	160.72	4.112	0.0039
Heartbeat -	Vacuum Cleaner	1.1351	243.02	6.217	<0.0001
Heartbeat -	Crashing Waves	1.2435	266.25	6.811	<0.0001
Heartbeat -	Wind	1.3040	279.18	7.142	<0.0001

Table 3.20: Table showing the thirty significant pairwise contrasts between emotionally resonant stimuli, from a total of 105 contrasts, when estimating differences in marginal mean arousal responses within a -3 to 3 range.

Emo. Res. Stimuli Resonance Contrasts		Effect Size	Estimate	T.Ratio	P.Value
Slow Breathing -	Underwater Bubbles	-0.7057	-142.78	-3.865	0.0101
Slow Breathing -	Car Engine	-0.8166	-165.21	-4.473	0.0008
Slow Breathing -	Cat Purring	-1.2869	-260.36	-7.049	<0.0001
Slow Breathing -	Muffled Conversation	0.6860	138.79	3.757	0.0151
Slow Breathing -	Heartbeat	-1.8558	-375.46	-10.16	<0.0001
Brushing -	Underwater Bubbles	-0.8235	-166.61	-4.510	0.0007
Brushing -	Car Engine	-0.9343	-189.61	-5.118	<0.0001
Brushing -	Cat Purring	-1.4046	-284.18	-7.693	<0.0001
Brushing -	Heartbeat	-1.9735	-399.28	-10.81	<0.0001
Underwater Bubbles -	Muffled Conversation	1.3917	281.57	7.623	<0.0001
Underwater Bubbles -	Heartbeat	-1.1500	-232.68	-6.299	<0.0001
Underwater Bubbles -	Scratching	0.7739	156.58	4.239	0.0023
Underwater Bubbles -	Wind	0.7335	148.41	4.018	0.0057
Car Engine -	Muffled Conversation	1.5026	304.00	8.230	<0.0001
Car Engine -	Dog Growling	0.7297	147.62	3.997	0.0061
Car Engine -	Heartbeat	-1.0392	-210.25	-5.692	<0.0001
Car Engine -	Scratching	0.8848	179.01	4.846	0.0001
Car Engine -	Vacuum Cleaner	0.6380	129.08	3.495	0.0372
Car Engine -	Wind	0.8444	170.83	4.625	0.0004
Cat Purring -	Muffled Conversation	1.9729	399.15	10.81	<0.0001
Cat Purring -	Dog Growling	1.2000	242.78	6.572	<0.0001
Cat Purring -	Raindrops	0.8560	173.19	4.689	0.0003
Cat Purring -	Scratching	1.3551	274.16	7.422	<0.0001
Cat Purring -	Small Stream	0.7944	160.72	4.351	0.0014
Cat Purring -	Train Tracks	0.9254	187.22	5.068	0.0001
Cat Purring -	Vacuum Cleaner	1.1083	224.23	6.071	<0.0001
Cat Purring -	Crashing Waves	1.0770	217.90	5.899	<0.0001
Cat Purring -	Wind	1.3147	265.98	7.201	<0.0001
Muffled Conversation -	Dog Growling	-0.7729	-156.38	-4.233	0.0024
Muffled Conversation -	Heartbeat	-2.5418	-514.25	-13.922	<0.0001
Muffled Conversation -	Raindrops	-1.1168	225.96	-6.117	<0.0001
Muffled Conversation -	Small Stream	-1.1785	-238.43	-6.455	<0.0001
Muffled Conversation -	Train Tracks	-1.0475	-211.93	-5.738	<0.0001
Muffled Conversation -	Vacuum Cleaner	-0.8646	-174.92	-4.735	0.0003
Muffled Conversation -	Crashing Waves	-0.8959	-181.25	-4.907	0.0001
Muffled Conversation -	Wind	-0.6582	-133.17	-3.605	0.0257
Dog Growling -	Heartbeat	-1.7689	-357.88	-9.689	<0.0001
Heartbeat -	Raindrops	1.4249	288.29	7.805	<0.0001
Heartbeat -	Scratching	1.9240	389.26	10.54	<0.0001
Heartbeat -	Small Stream	1.3633	275.26	7.467	<0.0001
Heartbeat -	Train Tracks	1.4943	302.32	8.184	<0.0001
Heartbeat -	Vacuum Cleaner	1.6772	339.33	9.187	<0.0001
Heartbeat -	Crashing Waves	1.6459	333.00	9.015	<0.0001
Heartbeat -	Wind	1.8836	381.08	10.32	<0.0001

Table 3.21: Table showing the fourty-four significant pairwise contrasts between emotionally resonant stimuli, from a total of 105 contrasts when estimating differences in marginal mean emotional resonance responses within a -3 to 3 range.

value adjustment, was conducted to assess the specific differences in valence and arousal between temperature levels. Two significant valence contrasts were found: both the warm (34°C) level and neutral (30°C) level were significantly more pleasant than the cold (24°C) level (see Table 3.15). One arousal contrast was found; emotionally resonant stimuli at 34°C were more arousing than at the neutral 30°C. Although these temperature contrasts were significant, the effect sizes (i.e. Cohen's D, the standardised difference in mean valence and arousal value between the temperature levels) of these contrasts were small (see Table 3.15).

When temperature was presented alongside abstract stimuli during Task 3, pairwise analysis found seventeen significant interactions contrasts between amplitude/temperature pairs (see Table 3.15). Temperature did not have a significant enough impact that any two contrasted pairs featured the same amplitude level; amplitude still dictated the majority of change, as one might expect given its main effect.

H1 - Quantitative Results Summary

The first hypothesis stated that warm thermotactile cues were expected to have a significant positive effect on valence and arousal. When presented in isolation, or alongside abstract vibrotactile stimuli, temperature had no main effect on valence. Temperature did have a main effect on arousal in isolation and pairwise analysis revealed that more extreme warm and cold temperatures were more arousing than neutral levels. When presented alongside emotionally resonant vibrations, temperature had a main effect on valence and arousal. *Post hoc* analysis found that the colder 24°C level was less pleasant than the neutral 30°C and warm 34°C, and that 34°C was more arousing than 30°C, although effect sizes were small. Overall, quantitative results support temperature's hypothesised positive impact on arousal and partially support the hypothesised positive impact on valence, specifically when presented alongside emotionally resonant vibrations.

Hypothesis 2 - Main Effects, Interaction Effects and *Post Hoc* Testing

H2 - Main and Interaction Effects

Hypothesis 2 expected that "*participants will find emotionally resonant vibrotactile stimuli with an expected temperature more resonant or dissonant depending on the temperature*". To investigate this, an ANOVA searched for main or interaction effects of temperature on emotional resonance when presented alongside emotionally resonant stimuli in Task 3. Temperature did not have a main effect on emotional resonance (see Table 3.22), but the stimulus presented did ($F = 22.98, df = 14, p < 0.0001$). There was an interaction effect on resonance between stimulus and temperature ($F = 1.592, df = 28, p < 0.0271$).

H2 - Post Hoc Testing

Following the observation of an interaction effect between temperature and stimulus, *post Hoc* testing was conducted to establish if different temperature levels changed the emotional resonance of certain stimuli. To test this, the data-set of emotionally resonant stimulus was split by each stimulus and the effects of temperature on the each stimuli were individually analysed using the *emmeans* package. Pairwise analysis for each stimulus featured internal P value adjustment, using *emmeans*, but as testing of each stimulus was conducted separately without automatic P value adjustment *between* tests, Bonferroni Family-Wise Correction was calculated and indicated an alpha of 0.0033. Three significant contrasts were found from a possible 45 (see Table 3.16). *Heartbeat* was significantly less resonant at 24°C than either 30°C or 34°C. *Small Stream* was significantly more resonant at 24°C than 34°C. Both of these stimuli became more resonant when presented at their expected temperatures (see Table 3.12), and less so when presented with a dissonant temperature.

H2 - Quantitative Results Summary

Quantitative analysis found three statistically significant interaction effect contrasts which support Hypothesis 2's assertion that an expected or unexpected temperature can improve or worsen the emotional resonance of vibrotactile stimuli. These results were not, however, part of a wider trend; only three significant contrasts from a total of fourty-five possible pairs were found and many other stimuli with an expected temperature like *Cat Purring* or *Car Engine* were not significantly affected by temperature presentation. Quantitative results suggest that, while the effect expected by H2 can occur, it is not widespread.

Hypothesis 3 - Main Effects, Interaction Effects and *Post Hoc* Testing

Hypothesis 3 stated that "*Stimulus resonance will positively correlate with stimulus valence and arousal*". To investigate this, a Pearson product-moment correlation test was used to search for correlations between emotional resonance and emotional response. A significant positive correlation was found between both resonance and valence ($cor = 0.2133, df = 898, p < 0.0001$) and between resonance and arousal ($cor = 0.2027, df = 898, p < 0.0001$), indicating that participants found stimuli for which they felt emotional resonance more pleasant and more attention-grabbing.

Hypothesis 4 - Main Effects, Interaction Effects and *Post Hoc* Testing

Hypothesis 4 stated "*Emotionally resonant vibrotactile stimuli will receive a wider range of emotional responses and qualitative feedback than abstract vibrotactile stimuli*". This can be ascertained by (1) observing the mean emotional responses to both abstract vibrations (see Table 3.17) and emotionally resonant vibrations (see Table 3.18) and (2) observing the quantity and range of qualitative comments regarding both categories of stimuli (see Table 3.23). The range of average valence responses to abstract stimuli was 0.28 (*F3A3*) to 0.58 (*F1A1*) on a -3 to 3 scale and the range of average arousal responses was 0.2 (*F1A1*) to 1.92 (*F3A3*). No abstract stimuli were rated with negative mean arousal. The ranges of affective responses to emotionally resonant stimuli were: average valence ranging from 0.03 (*Slow Breathing* / *Dog Growling* / *Scratching*) to 1.20 (*Cat Purring*) and average arousal ranging from -0.95 (*Slow Breathing*) to 1.37 (*Heartbeat*). Plotting these on a valence-arousal graph [184], nine stimuli were in the alerting and pleasant top-right quadrant and six in the bottom-right pleasant and calming quadrant (see Figure 3.17).

Emotional Responses to Emotionally Resonant Vibrotactile Stimuli

This experiment provided an opportunity to further investigate affective responses to a wider selection of emotionally resonant vibrations. The overall aim of these stimuli was to be calming and/or emotionally resonant, so quantitative analysis was used to search for stimuli which are significantly higher valence, lower arousal or more resonance than others.

Three ANOVAs were conducted to investigate the impact of temperature and stimulus on emotional response during the investigation of H1 and H2 (see Tables 3.14 and 3.22). These found that the emotionally resonant stimulus presented had a significant main effect on valence ($F = 4.418, df = 14, p < 0.0001$), arousal($F = 10.98, df = 14, p < 0.0001$) and emotional resonance ($F = 22.98, df = 14, p < 0.0001$).

Post hoc analysis of the main effect on valence found ten significant contrasts from a total of 105 (see Table 3.19 and Figure 3.17). All but one of these were *Cat Purring* being found to be significantly more pleasant than other stimuli. The one exception was *Crashing Waves* being significantly more pleasant than *Dog Growling*.

Thirty significant mean arousal contrasts between stimuli were found from a total of 105 (see Table 3.20). *Heartbeat* was significantly more arousing than every other stimulus in the set. Eleven contrasts were between *Slow Breathing* and other stimuli and in each case it was significantly less arousing. *Brushing* accounted for the remaining contrasts and was significantly less arousing in each one.

When testing for differences in emotional resonance between stimuli, 44 significant contrasts were found from a total of 105 pairs and a wider variety of stimuli were featured in the contrasts than in valence and arousal analysis. The least resonant stimulus in the set was *Muffled Conversation*, which was found to be significantly less resonant than 12 other stimuli. *Heartbeat* and *Cat Purring* had significantly higher resonance than twelve and eleven other stimuli respectively. *Car Engine* was significantly more resonant than seven other stimuli, but less resonant than *Heartbeat*. *Underwater Bubbles* similarly was more resonant than five other stimuli but also less resonant than *Heartbeat*. Certain stimuli, like *Slow Breathing*, *Dog Growling* and *Brushing* were found to be less resonant than all the many or all of the stimuli previously mentioned, except for *Muffled Conversation* (see Figure 3.17).

Task 3 - Temperature Stimulus Effects on Resonance	F	Df	P.Value
Stimulus	22.98	14	**<0.0001**
Temperature	2.889	2	0.0562
Stimulus / Temperature	1.592	28	**0.0271**

Table 3.22: Experiment 3 main effects of temperature and stimulus presented on emotional resonance. P values which indicate significant main effects and interactions effects are bold.

Vibration	Times Mentioned	Comments
Cat Purring	11	"Resonant" x 2, "Enjoyable" x 2, "Reminds me of my cat"
Heartbeat	9	"Resonant" x 3, "Enjoyable", "Unmistakable" x 2
Crashing Waves	3	"Resonant", "Water stimuli melded into one"
Dog Growling	2	"Not resonant"
Vacuum Cleaner	1	"Not resonant"
Train Tracks	2	"Made me happy"
Scratching	2	No comments
Raindrops	1	"Water stimuli melded into one"
Small Stream	2	"Water stimuli melded into one", "Felt like water"
Car Engine	1	"Reminded me of feeling the engine through the steering wheel"
Abstract Stimuli	4	"Annoying when too long", "Preferred Abstract Stimuli", "Nice and Regular", "Distinguishable"

Table 3.23: Table summarising how often during Experiment 3 interviews different vibrations were mentioned by participants and what specific comments were made about each stimulus.

Temperature	Preferred	Disliked	Comments
Hot	5	3	"Felt alarming", "Felt dangerous/worrying" x 2, "More alerting"
Cold	7	2	"Almost painful", "Felt sharper", "More alerting" x 2, "Numbed the hand", "Not that pleasant or arousing"

Table 3.24: Table summarising comments made about different temperature levels by Experiment 3 participants.

Vibration	Times Mentioned	Impact of Temperature
Cat Purring	2	Cold cat purring felt dissonant x 2
Heartbeat	8	Warm heartbeat felt nice/resonant x 2
		Cold heartbeat felt dissonant x 5
		Very aware of cool vs warm heartbeats
Bubbles	3	Warm bubbles felt boiling x 2
		Cool bubbles felt refreshing
Scratching	1	Cold made scratching more impactful
Small Stream	2	Cold water felt resonant x 2
Car Engine	2	Cold car engine felt dissonant
		Hot car engine felt resonant
Non-Stimulus Specific	26	Warm abstract stimuli felt like a dentist drill
		Vibration more impactful than temperature x 3
		Affected some stimuli x 3
		Liked some more based on temperature
		Preferred some stimuli when cold x 2
		Not very obvious change
		Didn't like cold with stimuli that should be warm
		Made some stimuli more or less realistic
		Cold stimuli less pleasant
		Warmth made stimuli more pleasant
		All were more arousing and noticeable
		Made a difference with stimuli I recognised
		Harder to pay accurately differentiate vibrations x 4
		Cold more attention grabbing
		Lost track due to so many combinations
		Stimuli closer to expected temperature more resonant x2
		Low frequency intense stimuli when cold felt hot
		Water stimuli made sense with cold or hot temperatures

Table 3.25: Table summarising comments made in Experiment 3 when participants were asked to discuss how thermal cues impacted their perception of and emotional response to emotionally resonant vibrotactile stimuli.

Qualitative Feedback

Following the three experimental tasks, each participant answered three interview questions to provide context and rationale behind their emotional responses to different stimuli. Participant responses were grouped by topic and sentiment and are discussed below.

Question 1: Did any particular vibration you experienced throughout the experiment stand out to you? If so, why?

While this experimental task asked participants to rate the emotional resonance of stimuli, they were also given the opportunity to highlight vibrations they found especially notable and why. Participant responses regarding different stimuli are summarised in Table 3.23. *Cat Purring* and *Heartbeat* were again most mentioned, as in Experiment 2, with participants finding them resonant and enjoyable. Four participants mentioned finding some resonant stimuli hard to distinguish from each other. Five found some stimuli hard to relate to outside of a number they found more resonant, which were often specified as more "rhythmic" stimuli.

Question 2: Which temperature did you prefer and why?

Participants were next asked to discuss their preferences for the different temperature levels they experienced, the results of which are summarised in Table 3.24. Opinion on temperature was split, with cool being slightly more preferred than warm, despite warm temperatures being significantly more pleasant based on valence response data. This variance in these qualitative responses might explain why temperature did not have large effect sizes on the emotional response to vibrotactile stimuli, in the few instances where it had a significant effect.

Question 3: Did you feel that changes in temperature changed how you felt about the vibrations?

The final question asked if participants felt that different temperature levels changed their experience with vibrotactile stimuli. A wide variety of responses and topics were recorded and are summarised on Table 3.4.6. When discussing general impact on emotional response, 17 participants felt temperature made a significant difference to their general perception, while three felt that the vibration had a stronger impact on their response or that temperature made little difference. This impact manifested in different ways. Four said that the addition made it harder to accurately perceive stimuli, particularly when the temperature was dissonant with the stimuli, and six that the addition of temperature changed how generally pleasant the stimuli felt.

While only three significant interactions on emotional resonance were found between stimuli presented at different temperature levels during quantitative analysis, this was a very strong theme in qualitative analysis. The effect of temperature on the resonance, and subsequently preference, of certain stimuli was a common theme in interview responses, with seventeen total comments recorded. Seven participants commented that warm temperatures made *Heartbeat* and *Car Engine* more resonant. While cold stimuli did prompt four comments that it made water-based stimuli more resonant, six comments focused on stimuli it made more dissonant, including *Heartbeat*, *Cat Purring*, *Slow Breathing* and *Car Engine*. Four comments were made that water stimuli like *Small Stream* and *Underwater Bubbles* could be resonant at either temperature, but it changed their meaning from "cold and refreshing" to "boiling".

3.4.7 Discussion

Experiment 3 observed how the addition of warm and cool temperature levels affected emotional responses to emotionally resonant and abstract vibrotactile stimuli. In addition, it tested emotional response to an expanded set of emotionally resonant stimuli informed by Survey 2 and directly observed emotional resonance for each stimulus when presented.

Hypothesis 1 Discussion

The first hypothesis stated that warm thermotactile cues would have a significant positive effect on valence and arousal, grounded in prior affective multimodal and thermotactile research [188, 230, 232]. Quantitative analysis found that temperature could have a small positive effect on valence only when presented alongside emotionally resonant stimuli,and a significant positive effect on arousal when experienced both in isolation and with emotionally resonant stimuli. When presented alongside emotionally resonant stimuli, however, the effect sizes on both were small.

A mixture of qualitative feedback about temperature's impact on valence and arousal was found. When asked which they preferred, five participants indicated warm stimuli and seven indicated cool stimuli, although when asked to give a reason for their choice participants tended to mention the arousal of thermal stimuli (see Table 3.24). Overall, Hypothesis 1 bore out when warm thermal stimuli were presented alongside emotionally resonant vibrations, but its effects on arousal were much more pronounced than on valence. Utilising thermotactile stimuli incurs significant practicality costs, due to the large size of the heat sink and need for good contact with a small heating element, and limits the flexibility of vibrotactile stimuli which can radiate through rigid objects with different sizes and form factors. The small effect size on valence, alongside the large positive effect on arousal (when lower arousal is desirable for calming stimuli), did not make a strong case for utilising thermotactile stimuli in future studies. If, however, thermal cues had a significant impact on emotional resonance, as posited by Hypothesis 2, there yet have been good justification incorporating them into the proposed social anxiety intervention.

Hypothesis 2 Discussion

Hypothesis 2 stated that participants would find vibrotactile stimuli more resonant or dissonant when presented along a temperature level which complements or contrasts expectations of the original sensation being evoked. *Post hoc* analysis found three significant contrasts in which stimuli with an expected temperature had their emotionally resonance improved or worsened when presented alongside a resonant or dissonant temperature. These results were not part of a wider trend, however; only three significant contrasts from a total of fourty-five possible pairs were found and many other stimuli with an expected temperature like *Cat Purring* or *Car Engine* were not significantly affected by temperature presentation.

Temperature impacting emotional resonance was a much stronger theme in qualitative feedback. It is clear from many participants comments that specific individuals felt all the stimuli with expected temperatures listed in Table 3.12 felt more resonant to them when presented with a matching temperature and *vice versa*. In addition, several people mentioned that water stimuli like *Underwater Bubbles* and *Small Stream* had their meaning impacted by temperature, from cool running water to hot boiling water. Twenty-one total comments were made which cited that temperature level impacted the emotional resonance of specific stimuli, but it is clear that, aside from three contrasts, these experiences did not constitute significant enough trends to produce a wider statistical trend. It can be inferred that participant relationships with specific emotionally resonant stimuli and temperature levels vary between individuals.

When considering both the quantitative interaction effect and qualitative feedback, the impact of temperature on emotional resonance described by Hypothesis 2 can be clearly observed, but not in a consistent manner across participants and stimuli. Depending on the participant and emotionally resonant stimulus, the addition of thermotactile stimuli could have a beneficial effect on emotional resonance. The lack, however, of a consistently strong impact on valence or resonance informed the choice not to use thermotactile cues in future work difficult, as the large heat sink and small heating element of the Peltier unit would disproportionately impact the ability to provide users with form factor and interaction flexibility.

Hypothesis 3 Discussion

Hypothesis 3 stated that stimulus emotional resonance would correlate with stimulus valence. This is supported by quantitative data, as a positive correlation between the two was found by many qualitative comments suggested that participants found stimuli pleasant and notable when they were also resonant, as well as by qualitative comments which linked stimuli enjoyment with the participant's emotional association (see Tables 3.23 and 3.4.6). These findings support the general approach taken by the thesis of leveraging emotionally resonant stimuli to elicit pleasant affective experiences. In addition, it suggests a similar effect may be taking place in the context of other interfaces with which users can make an emotional association, like social robots, providing evidence that this association may be responsible for the affective properties of said interfaces.

Hypothesis 4 Discussion

This experiment provided an opportunity to observe emotional responses and emotional resonance ratings to a wider variety of stimuli drawn both from Experiment 2 and user preferences indicated in Survey 2 (discussed in Section 4.3). Hypothesis 4 stated that a participant's emotional responses to emotionally resonant stimuli were expected to be more varied and have a wider range than to abstract stimuli. Emotionally resonant stimuli elicited a wider range of mean valence and arousal than abstract stimuli and seven emotionally resonant stimuli exceeded both the valence and arousal ranges of abstract cues, respectively. Notably, four emotionally resonant stimuli had valence scores above the maximum range of abstract stimuli and seven had lower arousal scores, important areas for producing calming and pleasant stimuli.

There was a large disparity in the amount of qualitative discussion between emotionally resonant stimuli (mentioned 34 times) and abstract stimuli (mentioned 4 times). While those who mentioned abstract stimuli uniformly said they enjoyed them or preferred them to emotionally resonant stimuli, far more participants mentioned the emotional resonance or their preference for emotionally resonant stimuli overall. These quantitative and qualitative findings supported Hypothesis 4: when compared to traditional abstract stimuli, emotionally resonant stimuli were successful in eliciting a wider range of emotional responses, including sensations with desirable higher valence and lower arousal. Additionally, Experiments 2 and 3 have shown that participants can form emotional connections with emotionally resonant stimuli and successfully associate them with past emotional experiences. These findings ratified the choice to utilise emotionally resonant vibrotactile stimuli as a personalisable, portable and calming haptic intervention in future studies.

Removal of Poorly Performing Emotionally Resonant Stimuli

Following this experiment, six emotionally resonant vibrations were eliminated from the selection offered to users for the next participatory prototyping study discussed in Chapter 5. The aim was to allow users to choose from a proven set of stimuli to suit their personal experiences. Stimuli were eliminated if they did not exhibit any of the desirable criteria of a calming, pleasant, emotionally resonant cue. These criteria were: low arousal, high valence or high emotional resonance and both quantitative and qualitative data informed these selections. *Vacuum Cleaner*, *Dog Growling*, *Muffled Conversation*, *Wind* and *Scratching* were all removed due to mean negative emotional resonance, low valence, and neutral and/or positive arousal. *Train Tracks* had somewhat positive valence (0.42), but positive arousal (0.38), as well as low resonance (0.12), and was also eliminated.

This left a set of nine stimuli for use in later studies. *Cat Purring* and *Heartbeat* exhibited the highest emotional resonance, alongside very high valence and arousal respectively, and were the most discussed stimuli in qualitative feedback. *Underwater Bubbles* and *Car Engine* exhibited high emotional resonance and valence. *Raindrops*, *Crashing Waves* and *Small Stream* exhibited relatively high mean valence scores (between 0.57 and 0.75, compared to a mean valence of 0.43 across all stimuli) despite neutral average arousal and emotional resonance. They also received 11 total qualitative comments discussing their ability to be emotionally resonant at different temperatures. While *Slow Breathing* and *Brushing* had negative average emotional valence they were retained for their relatively low negative arousal ratings (-0.95 and -0.57, compared to a mean arousal of 0.09).

Research Question 2 Discussion

Experiment 3 directly addressed Research Question 2: *Can thermal cues be used to enhance the emotional resonance and affective range of vibrotactile stimuli?* Temperature was observed to have significant main effects on valence, arousal and an interaction effect with stimulus presented on emotional resonance. Three significant contrasts revealed by *post hoc* analysis found that the warmer temperature level of 34°C tended to result in higher valence and arousal and more pleasant and alerting stimuli, but with a small average effect size. It also had a statistically significant effect on the resonance on two stimuli over three contrasts, in all cases resulting in stimuli being more emotionally resonant when presented at their expected temperature than the opposite, with qualitative comments highlighting instances where participants felt this effect for many other stimuli.

This shows temperature can have a positive impact on the perception on emotionally resonant vibrations, resulting in more pleasant and emotionally resonant, varying by participant. While this could motivate its inclusion in future experiments, the effect sizes and limited number of contrasts undermined this case. It was not evident from this experiment that temperature would have enough benefit to warrant the employing the thermotactile actuator in future studies, which would require users to hold the object in a specific way and require a specific form factor. Hence, it was decided not to pursue this modality in future work and focus on leveraging the portability and flexibility of vibrotactile actuators and stimuli.

3.5 Chapter 3 Discussion

This chapter featured a series of three experiments which explored and developed a novel category of affective haptic stimuli and laid the foundation for developing an intervention for social anxiety exposure therapy by leveraging novel pleasant emotionally resonant cues. The emotionally resonant stimuli to be tested in Experiment 2 required a longer duration to allow for detailed natural phenomena to play out and be comprehended, but it was unclear if changing the duration level from those used in prior work, which used ranged from 0.2-2 seconds, would impact emotional response. Therefore, Experiment 1 explored the potential impact of elongated duration of emotional responses to vibrotactile stimuli, replicating the stimuli and study design from prior work while comparing a short 2-second duration level to a long 20-second level. Duration had no statistical main effect on emotional response, but qualitative feedback repeatedly cited that 20-second stimuli caused adaptation and sensation-deadening effects. This informed the decision to use a duration of 10-seconds when testing emotionally resonant stimuli in Experiments 2 and 3.

Experiment 2 was designed to observe emotional responses to a novel category of affective haptics: emotionally resonant vibrotactile stimuli. Emotional resonance had been effectively utilised in other fields like affective sound and social robotics to elicit specific emotional responses and it was theorised it could be used to widen the previously observed narrow affective range of vibration. Emotional responses to eight vibrations generated from sound recordings of real-world phenomena were observed. While the average range of emotional response was similar to affective of abstract stimuli tested in Experiment 1, higher response variance and strong individual qualitative feedback was observed. This may be accounted for by the individualistic nature of users' relationships with emotionally resonant stimuli as they rely on personal prior experiences. Participants found reported finding different stimuli emotionally resonant and subsequently had different emotional responses based on their association with the original sensation evoked.

A third experiment was designed to build on this initial exploration, testing a larger set of emotionally resonant vibrations alongside the abstract stimuli used in Experiment 1. Emotional resonance was directly recorded after each impression and thermotactile stimuli were trialled alongside the vibrations to discover if different temperature levels impacted either emotional resonance or emotional response. Temperature had a small positive impact on the valence emotionally resonant stimuli and, in three contrasts, it was observed that combining a stimulus with a 'expected' temperature (e.g. a small stream is expected be cool, while a heartbeat is expected to be warm) increased its emotional resonance and *vice versa*. Due to the limited influence of these effects and the size and impracticality of the apparatus, however, thermotactile stimuli were not utilised in future studies. The wider selection of emotionally resonant stimuli exhibited a wider range of emotional responses than abstract stimuli. The nine stimuli which were able to exhibit the desirable traits for pleasant and calming emotionally resonant cues - low arousal, high valence or high emotional resonance - were retained for use in Experiments 4 and 5 in Chapter 5. Six poorly performing stimuli which did not exhibit these traits were removed from the set.

3.6 Conclusions and Research Questions 1 and 2

This chapter directly laid the foundation for developing an intervention for social anxiety exposure therapy by leveraging novel pleasant emotionally resonant haptic stimuli by answering Research Question 1 and Research Question 2.

Research Question 1: Can single-actuator vibrotactile stimuli be emotionally resonant of real-world sensations?

Qualitative data from the second and third experiment confirm that vibrotactile stimuli produced by a single actuator can be emotionally resonant of real world sensations. Participants were able to relate stimuli to their sensations of origin and form positive or negative emotional associations with them. Emotional resonance was quantitatively reported in Experiment 3 and five stimuli achieved positive emotional resonance ratings, of which the most resonant were *Cat Purring* and *Heartbeat*. It was clear from qualitative feedback and quantitative data that reactions to emotionally resonant stimuli varied greatly from person to person; a stimulus which one participant finds pleasant and resonant may feel like meaningless buzzing to another. Allowing users to trial and choose from a set of proven emotionally resonant stimuli stands the best chance of providing each user with an affective vibrotactile experience they find pleasant and calming which can then be utilised during social exposure.

Research Question 2: How do thermal cues affect responses to emotionally resonant vibrotactile stimuli?

The results of Experiment 3 show that thermal cues can have a significant impact on the valence, arousal and resonance of emotionally resonant vibrotactile stimuli. Warmer temperatures had a positive impact on valence and arousal, but with small effect sizes. Temperature also had an effect on the emotional resonance of two stimuli. *Heartbeat* was less emotionally resonant at a cool temperature than neutral or warmer levels and *Small Stream* was more resonant when cool, better evoking cold water. This represented only three contrasts from a possible 45, however, demonstrating it did not have a strong widespread effect on the stimuli set or even any of the other five stimuli with an expected temperature (see Table 3.12). While it is possible for temperature to have interesting effects on emotionally resonant stimuli, it was not very impactful.

Chapter 3 detailed the development and validation of a new category of affective vibrotactile stimuli with the potential to provide pleasant, calming and emotionally resonant experiences to users via a simple, discreet vibrotactile actuator. These are the emotionally resonant cues which would be incorporated into an affective haptic intervention for social exposure . Chapter 4 details a pair of surveys which focused on the specific needs and wants of socially anxious users. These studies would inform and validate the selection of emotionally resonant presented to participants in Experiment 3, then be used to shape the participatory prototyping approach adopted alongside socially anxious users in Chapter 5.

Chapter 4

User Behaviours and Affective Preferences

4.1 Introduction

Chapter 3 discussed the development of novel emotionally resonant vibrotactile stimuli. This chapter took the next step of informing how these stimuli could be delivered to socially anxious users during social exposure. Using these stimuli as a calming intervention is grounded in the cognitive-behavioural model of social anxiety -allowing people to regulate their emotions by redeploying their attention from their physiological anxiety symptoms to an external and calming sensation or by cueing up alternative positive thoughts- and the restrictions of social exposure as a setting, as they can be delivered discreetly without interrupting conversation or provoking stigma. This theoretical approach, however, does not account for the specific requirements and preferences of real socially-anxious users when using the proposed affective haptic intervention.

Chapter 4 discusses two surveys which investigated how socially anxious users currently attempt to manage their anxiety and how affective haptics could act as a calming intervention. The first survey investigated how socially anxious users attempt to regulate their emotions with safety behaviours and how they currently experience and perceive affective touch. The second survey investigated user preferences for calming haptic sensations in different social scenarios in order to inform and validate the wider selection of emotionally resonant stimuli used in Experiment 3. It also gathered texture and form factor preferences, which informed the inclusion of a rapid participatory prototyping approach used before then conducting Experiment 4. These surveys were conducted and analysed between Experiment 1 and 3, provided firsthand understanding of the lived experiences and preferences of socially anxious users, subsequently informing the design of the experiments 3, 4 and 5 by answering Research Question 3:

RQ3: Which calming real-world experiences would users prefer emotionally resonant vibrotactile stimuli to evoke and what factors would impact their use in social settings?

4.2 Survey 1: Affective Regulation and Affective Touch Preferences of the Socially Anxious

Survey 1 assessed the potential applicability of an affective haptic intervention by observing how socially anxious users currently attempt emotion regulation and how they experience affective touch when anxious. This survey provided first-hand insight into the lived experiences of the target users and informed whether an affective haptic intervention that necessitates tactile interaction is compatible with user's current emotional regulation habits and affective touch preferences.

4.2.1 Social Anxiety Screening

To gain understanding of the requirements of socially anxious users, and later assess the efficacy of the proposed haptic intervention, a tool was needed to screen participants for social anxiety. The Social Interaction Anxiety Scale (SIAS) was chosen for this purpose. Designed by Mattick and Clarke [135], the SIAS measures anxiety experienced due to social interactions and is publicly available and a widely used tool in many fields including psychology and HCI [58, 62, 110, 137, 172, 180]. The scale features twenty items answered on 5-point Likert scales from 0 to 4. The items are self-statements postulating how the participant may feel they respond to different scenarios, which participants will agree or disagree with. Higher scores indicate a higher level of social anxiety during social interactions and a score of 34 or more indicates the participant is likely to be socially anxious [135], with Mattick and Clarke finding that socially anxious individuals scored an average of 34.6 on the SIAS when compared to an average of 18.8-19.0 for community or undergraduate population samples.

4.2.2 Methodology

The survey contained three sections [B.4.1]. Section 1 assessed participant social anxiety and so presented the SIAS, a total of twenty multiple choice questions. Section 2 investigated how participants used and perceived different safety behaviours when feeling stressed or anxious. Safety behaviours are emotion regulation actions which individuals may use to reduce the perceived danger of fearful situations (see Section 2.2.2). In total, Section 2 presented twenty-seven multiple choice questions with three optional additional questions when participants chose to suggest an additional safety behaviour. Participants were first asked to indicate how often they performed each of nine different pre-selected safety behaviours (see Table 4.1) and indicate a different behaviour they use instead, if applicable. This was done on a 5-point Likert scale with the following categories: 'Never', 'Wanted to' (they desired to perform the behaviour but felt it was not appropriate), 'Occasionally', 'Regularly' and 'Often'. Participants were then asked to indicate if they were more likely to perform each of these safety behaviours in public, private, either or neither. Finally they were asked to how calming they found each safety behaviour on a 5-point Likert scale from 'It makes me feel significantly less calm' to 'It makes me feel significantly more calm'.

Social Anxiety Safety Behaviour Selection	
1. I try to find space to be alone	2. I avoid making direct eye contact
3. I focus on my phone or some other device	4. I fidget with my clothes, a toy, or other object
5. I avoid speaking and stay quiet as possible	6. I start speaking far more than usual
7. I reach out to a pet or other animal	8. I reach out to touch or hug a friend
9. I reach out to touch or hug a family member or loved one	10. I perform some other action (indicate below)

Table 4.1: Table listing ten suggested safety behaviours used in Survey 1. Participants were asked to indicate how often they used the behaviours, if they preferred using them publicly or privately, and if they found them calming to perform.

Section 3 featured a total of eleven more questions, nine multiple choice and two written, and further investigated how participants perceived affective touch. First, they were asked to rate agreement with the statements 'I find it calming to reach out and touch friends/my partner/a family member/a pet or other animal/a possession' on a 5 point Likert scale between 'Not at all characteristic of me' and 'Extremely characteristic of me'. Second they were asked if they found having touch initiated upon them by a friend/partner/family member/pet comfortable or uncomfortable on a 5-point scale. Finally, they were asked to write whether they found sharing social touch in public or private more comfortable and why.

The survey had two hypotheses related to the two main sections: investigating the safety behaviours currently used by anxious users, and how these users these currently perceive affective touch in social settings:

H1: Respondents would most often utilise safety behaviours that avoided social interaction;

H2: Respondents would prefer affective touch when initiated in private.

Hypothesis 1 expected that participants would utilise actions that allowed them to avoid direct social contact, such as avoiding eye contact or speaking less. If true, this would highlight the need for alternative emotion regulation methods that enable social interaction. Hypothesis 2 described how participants were expected to prefer affective touch in private, away from social stigma, and when it was initiated upon them instead of by them, reducing the need for social pro-activeness. If these statements bore out it would also motivate the need for affective touch which can be delivered to the user to provide comfort in public settings. In addition to these hypotheses, this survey would also provide insight whether participants already found affective touch calming and if this varied between touch shared with different people, pets or objects. If participants do find affective touch calming but lack reliable or comfortable access to it, this could be addressed by a haptic intervention.

4.2.3 Participants

Eighty participants completed the survey (46 female, 27 male, 7 other; average age = 28.9y, σ = 12.6). Fifty-four participants scored 34 or higher on the SIAS (30 female, 18 male, 6 other; average age = 28.9y, σ = 10.1), indicating they were likely to suffer from social anxiety and responses from this socially anxious subset of participants are reported in the results. Participants were recruited using university, email, social media and physical advertising channels. People over the age of 18 with full tactile capabilities were eligible to participate in the survey which was open for new participants for several weeks.

4.2.4 Procedure

The survey was hosted on the JISC Online Survey service[1]. Participants were presented with an information sheet and consent form which they had to progress through before commencing the survey. The survey took between 10 and 15 minutes to finish and completion of the survey entered participants into a prize draw for a £40 Amazon voucher which was randomly awarded to one participant by email once the survey closed. The full survey can be found in the Appendix [B.4.1].

4.2.5 Results

Safety Behaviour Prevalence

Participants were asked how often they used different safety behaviours during stressful situations in the last two weeks. For seven of the nine safety behaviours (all except ’Touch with a friend’ and ’Touch with a family member/loved one’), the majority reported using them at least occasionally (see Figure 4.1). While none of these safety behaviours were used by all participants, every behaviour was performed or desired by at least 56% of respondents except for ’I reach out to touch or hug a friend’ (45%). The three most prevalent behaviours, performed ’Regularly’ or ’Often’ more than 55% of the time, were activities which allowed avoidance by the user: ’Find space to be alone’ (59%), ’Focus on phone/device’ (59%) and ’Avoid direct eye contact’ (55%).

Along with focusing on a device, ’Fidgeting with clothes, a toy or other’ was also used regularly or often by 53% of respondents. These two behaviours are both pre-existing tactile interactions and represented the possibility for haptic augmentation of existing habits, reducing the need for users learn a new interaction when using a calming haptic intervention. 77% respondents found themselves speaking less during stressful situations at least occasionally, and 53% found themselves speaking more. The two least performed safety behaviours were affective touch based, ’Reach out and touch a friend’ (at least occasionally performed by 45%) and

[1]JISC Online Surveys. https://www.onlinesurveys.ac.uk/

’Reach out and touch a family member or loved one’ (42%). Touching a pet or animal was, however, more prevalent (at least occasionally performed by 57%). It may be the case that initiating affective touch with people is either not perceived as calming, or as actively anxiety-inducing as it necessitates further social interaction and is non-discreet. Touch with a pet, however, does not have an interpersonal component, although pets are not always available to interact with, particularly in public. These possibilities would be explored later by the survey.

Behaviours Performed in Public Vs Private

Participants were asked if they were more likely to perform certain behaviours in public, private, either or neither (see Figure 4.1). The first five actions listed - avoiding eye contact, speaking, finding space to be alone, fidgeting with clothes or objects and focusing on a phone or device - were all more likely to be performed in public than in private. This may indicate that respondents believe these avoidance behaviours have more comparative utility in public and less familiar surroundings or social situations, where escape is more desirable. Participants more often performed affective touch behaviours and speaking more in private settings, rather than public settings: between 22% - 31% of respondents were more likely to perform these actions in public versus between 9.2% - 15% in private. These four behaviours were also generally less used, with participants responding ’Neither’ between 39% - 55% of the time. This could indicate that participants are concerned that these social actions are less acceptable or more likely to draw social attention in public.

Safety Behaviour Calming Effects

Only three behaviours were rated as ’More Calm’ or ’Significantly More Calm’ by more than 50% of participants: ’Find space to be alone’, ’Focus on phone/device’ and ’Touch pet/other animal’ (see Figure 4.1). This reveals a gap between prevalence and perceived efficacy of these safety behaviours; seven of the nine behaviours were performed by respondents at least occasionally in the last two weeks, but four of these were not calming for most people. This suggests that some safety behaviours are being performed instinctively or under the illusion they will reduce anxiety, rather than positive past experience to that effect. For example, 74% of participants performed (or wanted to) ’Speak more often’, but 59% found it to be less calming. The most effective calming behaviours, finding alone space, is also a problematic as it inhibits the social exposure core to most therapy programs.

Other avoidance actions, avoiding eye contact and avoiding speech, were cited as calming or significantly calming by 42% and 34% if respondents respectively. 46% of respondents found fidgeting with their clothes or some other object calming, an interaction which could potentially be improved with calming haptic augmentation and does not necessitate avoiding or interrupting conversation.

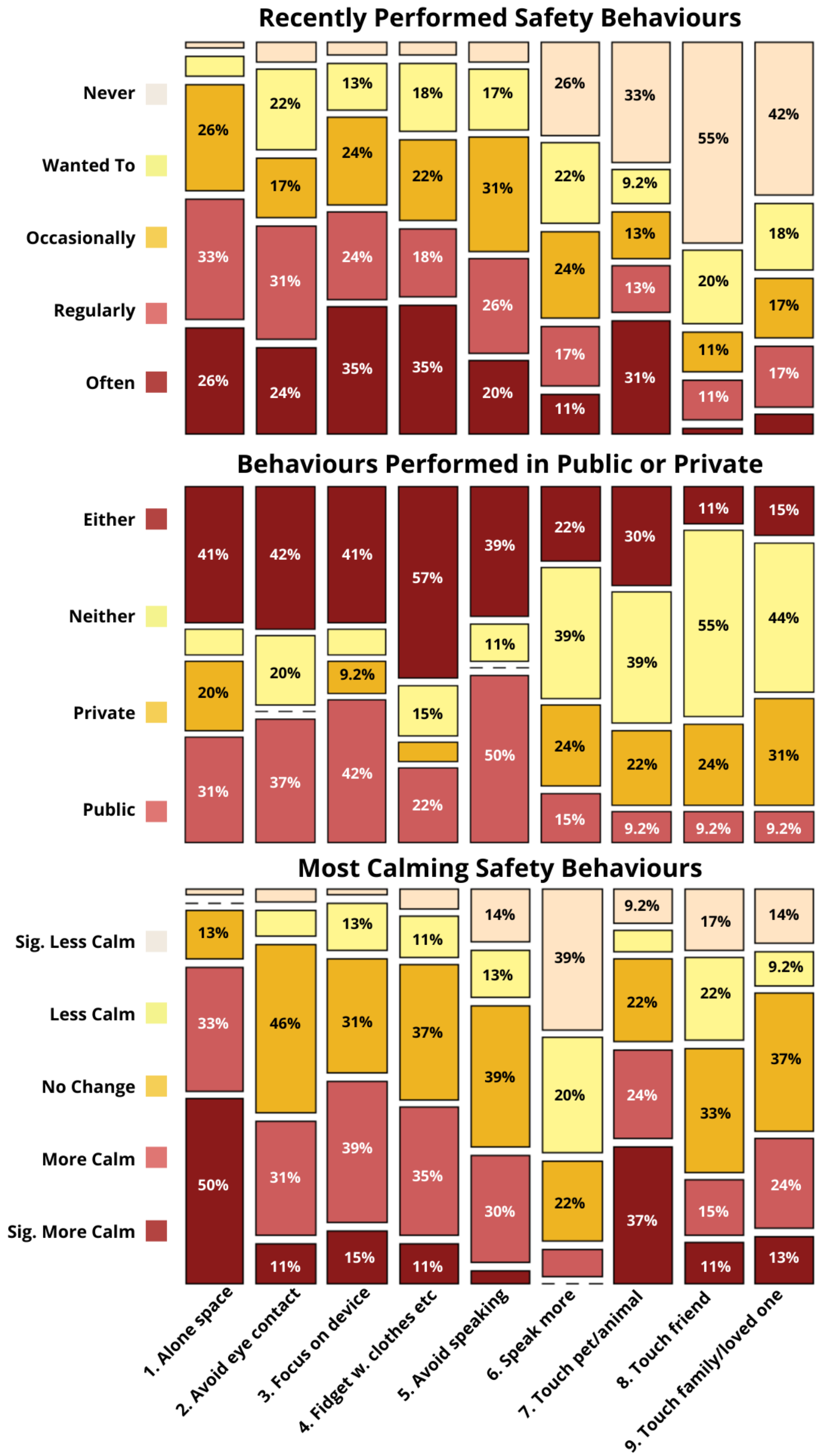


Figure 4.1: Three mosaic plots showing the proportion of different responses by socially anxious participants when asked to indicate how often they performed nine different safety behaviours, if they performed them more often in public or private and which they found more calming.

Respondent Initiated Calming Touch

When initiated by the participants, all affective touch categories were reported as at least slightly calming in a minimum of 50% of responses (see Figure 4.2). 'Touch with a partner or loved one' was the most calming, with 65% rating it 'Very Calming' or 'Extremely Calming', followed by 'Touch with a pet/other animal' with 66%. 'Touch with a family member' was more often rated as slightly calming (24%) or moderately calming (24%). 'Touch with a friend' was most cited as not at all calming (50%) and was otherwise more rated slightly calming than any other category (17%), indicating that participants were likely to either find it actively unhelpful or only somewhat helpful. Responses to how calming 'Touch with a possession' was were somewhat evenly distributed with between 18-22% choosing each rating. This suggests meaningful improvement could be achieved with calming haptic augmentation of held objects.

Respondent Received Calming Touch

When the affective touch sensations were received, rather than initiated, every option was rated as more calming than before. The most calming were touch from a loved one/partner and touch from a pet/animal. The biggest contrast between initiated and received touch was touch with a friend. Initiating touch with a friend was not considered calming by 50% of participants, but when receiving it was comfortable for all but 11%. This may be because touch which is received can already be assumed to be desirable in that social interaction, the receiver need not worry that the shared touch is unwanted or a *faux pas*, as they might do if they tried to initiate touch, but it may also be due to a difference in scales for each question, which makes comparing these questions difficult. Touch with an object was omitted from received touch as participants necessarily have to choose to touch an object and cannot independently receive it in most cases and this was highlighted by pilot testers.

Public Versus Private Calming Touch

When asked if they prefer affective touch in public or in private, 50% of respondents wrote private, 24% wrote either, 4% wrote public and 4% wrote neither. Three prevalent themes were identified when participants were asked to comment on why they gave these responses. The largest theme, drawn from comments by 14 participants, was preferring private touch because participants were concerned, embarrassed or self conscious about sharing touch in front of other people who may observe or judge them. One wrote:

> "Sharing touch in private feels true. Sharing touch in public can feel weighted with other people's views. Is this touch to show possession to others for example, is this touch making others uncomfortable, do I feel I have to respond to touch because other people are here?"

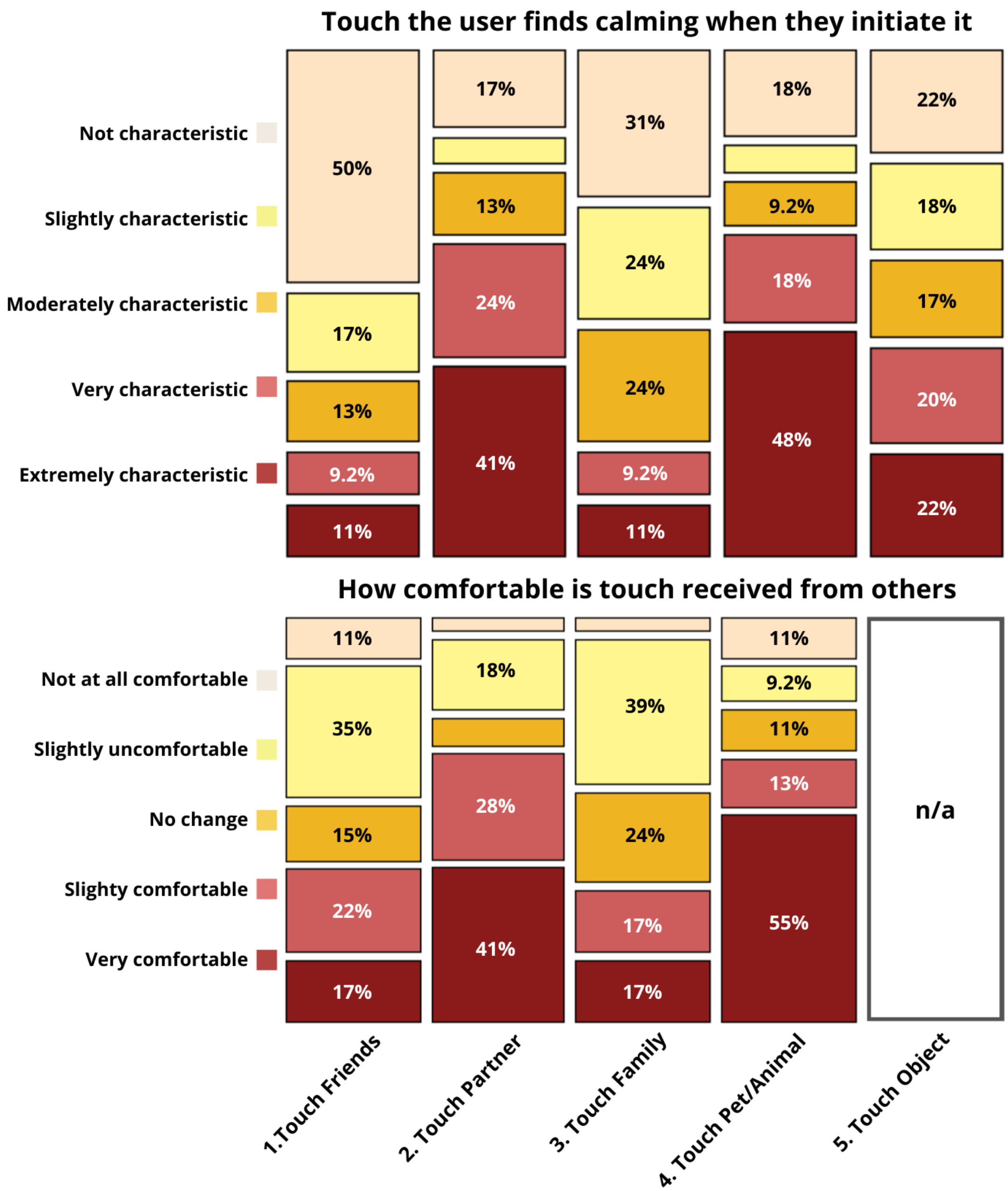


Figure 4.2: Two mosaic plots showing the proportion of different responses by socially anxious participants when asked to indicate how often calming they found five different kinds of affective touch when initiating them and how comfortable they were receiving four kinds of affective touch from others.

Five participants highlighted that they felt privacy befitted the intimacy of shared touch and allowed them to be more intimate than they could in public.

> "Because it is more intimate and I can be myself."

> "It generally comes with a sense of intimacy."

Five others wrote that they either intrinsically feel, or were raised to feel, that public touch is not acceptable or something they want to experience. For example two participants wrote the following:

> "I don't like to give people any indication that I like or want to be touched in any capacity."

> "I don't like Public display of affection <smiling emoji>. Actually I don't quite know why, probably because I was taught by my parents you don't do it. So I don't do it. Also it's so precious to me I don't want anybody to share these moments of intimacy <smiling emoji>."

4.2.6 Discussion

Survey 1 acted as an initial direct observation of how the needs and wants of socially anxious users may affect the applicability of a calming haptic intervention for social exposure. The survey demonstrated how often participants currently use different safety behaviours and how effective they found them, potentially motivating the need for calming alternatives and indicating which prominent pre-existing actions could be augmented with haptic stimuli. It also provided insight into how calming participants already perceived affective touch and what factors it depending on, highlighting how a future intervention could serve users better than traditional touch interaction.

Hypothesis 1 stated that respondents would utilise safety behaviours that allowed social avoidance more than others. This was strongly, although not absolutely, supported by the data. When asked which safety behaviours they had used, and how often, in the last two weeks during stress scenarios, four of the five safety behaviours were most often rated as used 'Regularly' or 'Often' by socially anxious participants were behaviours which allowed partial or total avoidance of social interaction. These were: 'Finding space to be alone' (used regularly or often by 59% of respondents), 'Avoiding direct eye contact' (55%), 'Focusing on a phone or other devices' (59%) and 'Avoid speaking and stay quiet as possible' (46%). The prevalence of avoidance behaviours highlights the needs for alternate intervention as these behaviours can inhibit social exposure and thus exposure therapy [23, 148, 183]. The outlier was 'Fidget with my clothes, a toy, or other object' (53%), which leverages attentional redeployment in a same manner way as this project's proposed intervention, but without an active calming haptic component.

The finding that holding a device or fiddling with clothes or an object are prevalent safety behaviours provides an opportunity for augmentation with calming haptics without requiring new interactions to be learnt by users.

The second hypothesis postulated that participants would prefer affective touch to be received and private, rather than initiated by them and in public. This partially bore out in the data. Over 12 times more participants indicated they preferred private affective touch to public touch, citing concerns of being observed by others and intimacy. This result motivated the design of an affective haptic intervention by indicating that some participants are currently impeded from receiving calming affective touch in public by fear of observation, social stigma or overt displays of intimacy. A discreet haptic interface provides an alternative affective touch modality which avoids these issues. In particular, respondents indicated that they found touch with a pet or animal calming, a result which corroborates the high valence exhibited by the emotionally resonant *Cat Purring* stimuli used throughout the experiments.

This survey provided motivation to further pursue the development of a calming haptic intervention for use during social exposure after its findings suggested socially anxious users most often use non-calming or avoidance-based behaviours and avoid calming affective touch actions due to social scrutiny or availability. A haptic intervention could be discreetly used to a provide calming sensations for attentional redeployment without necessitating the avoidance of a social situation or being directly observed and scrutinised by others. It also contributed understanding toward answering Research Question 3 by suggesting that three factors that impact user preference for affective touch are: whether it can be observed by others and whether the entity touched is a human, animal or object. Following this, the next survey aimed to inform the design of a calming haptic intervention by understanding socially anxious users' preferences for different calming haptic sensations.

4.3 Survey 2: User Suggestions for Relaxing Sensations in Different Social Scenarios

Survey 2 was used to define the design space for a wider set of emotionally resonant vibrotactile stimuli to be evaluated in Experiment 3. A core theme that we identified from Experiment 2, where emotionally resonant stimuli were first empirically tested, was that emotional responses to these stimuli was dependant on individual preferences and experiences. Each stimulus could be emotionally resonant, and as a result pleasant or unpleasant to experience, for some participants, but not for others. While it was not possible to present every possible calming sensation as an emotionally resonant vibration, evaluating a wider range of stimuli allowed for the construction of a stimuli set more likely to contain at least one vibration suited to each individual's preferences. The results of Survey 2 informed which stimuli to include in this broader evaluation conducted during Experiment 3 and provided further insight how other factors, such as social setting, impacted users preferences and which textures the proposed haptic intervention could employ.

4.3.1 Methodology

The survey [B.5.1] was primarily structured around four social scenarios which participants were asked to imagine themselves within (see Table 4.2). For each scenario, participants were asked to suggest auditory and haptic stimuli they may find calming. Whilst our focus was on affective haptics, we included audio as Experiment 2 found that haptic stimuli derived from audio samples could be emotionally resonant and allowed participants to suggest more sensations they have lived experience with, while revealing the wider calming experiences they wish to experience.

After suggesting stimuli through open text responses, respondents were then asked to choose multiple options from a predefined selection of eighteen stimuli that may also be relaxing (listed in Table 4.5). These were drawn from the stimuli used Experiment 2 and other stimuli which had been successfully presented via the Haptuator during exploratory pilot testing. This question produced further data on which experiences participants wanted and gave them the option to register interest in stimuli they had not considered.

Four potentially stressful social scenarios were designed that varied in two aspects: public vs private space, and intimate vs non-intimate relationships (see Table 4.2). The aim was to understand how participant preferences for calming sensations may vary depending on social setting. These scenarios were chosen to represent a mixture of public, private, intimate and non-intimate situations. Familiar settings and relationships helped participants imagine themselves in those scenarios, or recall past experiences. For each scenario, we asked "If you could choose to feel any touch sensation or hear any sound to relax you in this scenario, what would you choose?".

	Intimate	**Not Intimate**
Private	Important discussion with a partner at home regarding relationship.	Asked unexpected questions in a job interview.
Public	One-to-one discussion with a friend at a cafe over a serious matter.	Sitting in a bar in an unfamiliar group of people.

Table 4.2: The four social scenarios participants used, each designed to be either private or public and intimate or not.

Following the social scenarios section, participants were asked to suggest textures they found pleasant and objects they fidgeted with when stressed. Understanding these preferences for haptic experiences directly informed the participatory prototyping approach taken in later participatory prototyping, discussed in Chapter 5, where participants were asked to construct personalised haptic comfort objects from which the calming stimuli would emanate. The SIAS was administered at the end of the survey to assess if the participant was likely to be socially anxious.

This survey was exploratory in nature, designed to map haptic sensation preferences and better inform which vibrotactile stimuli, textures and form factors participants should be presented with in Experiments 3 to 5. There were, however, prior expectations for the some aspects of the results based on the findings of Survey 1, Experiment 2 and prior work. Two hypotheses described how changes in social setting were expected to impact affective preference and which broader categories of haptic sensation would be most prevalent:

H1: Respondents would prefer social touch in private and intimate environments;

H2: Pet-touch sensations would be the most prevalent social touch preference;

Hypothesis 1 is grounded in results from Survey 1, in which participants indicated they found social touch in public less comfortable. Survey 1 also found that animal touch was the most performed and preferred social touch variants and Experiment 2 found that *Cat Purring* was one of the most pleasant emotionally resonant stimuli, informing Hypothesis 2. Finally, Survey 2 contributed to answering Research Question 3 by eliciting affective haptic and auditory preferences from users, observing how different social settings may impact these preferences and informing which stimuli, textures and form factors were presented to users in future experiments when aiming to provide personalisable calming handheld objects.

4.3.2 Participants

Eighty-one participants completed the survey (48 female, 29 male, 4 other; average age = 38.7y, σ = 14.0). Twenty-six participants scored 34 or higher on the SIAS, suggesting only 32.1% of respondents were likely to be shy or socially anxious. As the goal of this survey was to elicit a wide range of affective touch preferences, data from all 81 respondents were included in the results, but any significant differences between socially anxious and non-socially anxious participants' preferences for pre-selected stimuli was reported.

4.3.3 Procedure

Survey 2 followed the same procedure as Survey 1 in terms of recruitment, participant eligibility, estimated completion time and payment (see Section 4.2.3). Participants were again presented with an information sheet and consent form before commencing the survey.

4.3.4 Qualitative Analysis Methodology

To understand the open-ended text response data given by participants, an open-axial-coding analysis approach was adopted, based on thematic analysis. Thematic analysis is "a method for identifying, analysing and reporting patterns (themes) within data" [40]. It is a flexible and diverse methodology with multiple interpretations and permutations, but this thesis follows the coding procedure outlined by Braun and Clarke in 2013 [40] (see Figure 4.3).

Phase	Description of the process
1. Familiarizing yourself with your data:	Transcribing data (if necessary), reading and re-reading the data, noting down initial ideas.
2. Generating initial codes:	Coding interesting features of the data in a systematic fashion across the entire data set, collating data relevant to each code.
3. Searching for themes:	Collating codes into potential themes, gathering all data relevant to each potential theme.
4. Reviewing themes:	Checking if the themes work in relation to the coded extracts (Level 1) and the entire data set (Level 2), generating a thematic 'map' of the analysis.
5. Defining and naming themes:	Ongoing analysis to refine the specifics of each theme, and the overall story the analysis tells, generating clear definitions and names for each theme.
6. Producing the report:	The final opportunity for analysis. Selection of vivid, compelling extract examples, final analysis of selected extracts, relating back of the analysis to the research question and literature, producing a scholarly report of the analysis.

Figure 4.3: Table describing the phases of thematic analysis. Extracted from [40].

This procedure involves assigning semantic codes that describes the data in a meaningful way, then considering how these codes could be grouped into descriptive themes which highlight some larger trend in the data [40, 186], although in this case, given the short and lower-detail responses to this survey (when compared to an interview for example) the higher-level results were reported more quantitatively, rather than using wholly descriptive themes. Where appropriate, codes were reused and adapted to establish consistent coding schemes. Two cycles of iterative coding were conducted. In each cycle and for each question, participant responses were assigned codes which categorised described their responses. These codes and their responses were grouped onto virtual notes and laid out on a virtual tabletop in Microsoft OneNote, from which higher-level codes and themes were identified. To increase the validity of the findings and reduce the impact of one researcher's singular interpretation skewing the analysis, a pair of researchers both conducted this process and independently without knowledge of each other's coding and created individual coding schemes. They then collaborated to synthesise these schemes into one. Both then re-coded the data set with the new combined scheme and then again met in a synthesis meeting to produce the final scheme of code and themes. A set of four thematic maps were then created (see Figure 4.4) to visualise the data for each social setting. We used the same process to codify the responses to questions about texture, objects and relaxing behaviours, expanding the set of codes obtained from the social scenario questions. Finally, we also analysed the choice from pre-selected stimuli list by counting their number of occurrences and reflecting on how they fit into the schema that we produced during our analysis of participant suggestions.

4.3.5 Result

Sixty-five codes were identified in the final coding scheme, drawn from 567 responses: i.e., 81 participants $\times$ 7 questions (4 scenarios plus textures, objects, activities). 40 of these codes were from responses to the social scenario questions (see Table 4.3), with an additional 25 identified for the suggested textures, fidgeting objects and relaxing behaviours. A new individual code was assigned if mentioned by several participants, otherwise responses were grouped into a larger code. For example, many of the objects participants said they fidgeted with were mentioned only once, whereas objects mentioned multiple times were assigned a new code (e.g. Stress Ball). Related codes like 'Hand' or 'Hug' would be grouped into larger codes like 'Human Touch'. From these, we identified four high level themes that represented different categories of experience which participants wished to experience when prompted for suggestions:

Social Social contact and experiences;

Natural Auditory and tactile experiences from nature;

Human Experiences with, and from, the human body;

Artificial Sensations from human-made objects or experiences.

Some codes were shared between two high-level codes. ‘Human’ and ‘Social’ shared the ‘Human Touch’ and ‘Human Voice’ codes. Similarly, ‘Natural’ and ‘Social’ shared the ‘Animal’ code, which was often (but not always) linked to animals with whom participants had a close relationship (i.e., family pets). Six codes were defined as prominent recurring attributes: ‘Background Sound’, ‘Soft’, ‘Warm’, ‘Stroking’, ‘Repetition’, and ‘Pressure’ (see Table 4.4). These were not distinct to any one higher level experience, but an attribute of many. For example, ‘Soft’ is an attribute of many codes including ‘Fabrics’, ‘Animal Touch’ and ‘Human Touch’.

There was a wide array of suggestions and the prevalence of each code across all scenarios is shown on Table 4.3. This informed how broad the range of user preferences for calming stimuli can be and which sensations were most prevalent (and therefore desirable for haptic emulation) The results and thematic map for suggestions preferences for each social scenario will now be discussed alongside specific examples, revealing how differences in social closeness and setting affected participant preference.

Job Interview Scenario (Private, Not Intimate)

In this scenario, we asked participants to imagine themselves being asked unexpected questions in a job interview, representing an anxious, private and not intimate social situation (see Figure 4.4). The largest experience theme was *Artificial* experiences, suggested 33 times. The largest code within this theme was *Music* (suggested 11 times), with varied specifications including “soothing”, “ambient”, “classical” and “slow beat”. Other artificial sound suggestions either referenced ambient sounds like a ticking clock or ceiling fan. Artificial tactile experiences were also suggested, with most codes grouped into *Fidget Objects* (8), *Fabric* (6) and holding a *Warm Mug* (4). Examples included holding a “soft ball” or “stress ball”, touching “soft fabric” or “a material like velvet or satin” or more abstract desires like “texture on a hard surface”.

Code	**Interview**	**Bar**	**Cafe**	**Home**
Artificial	33	42	36	23
→ Artificial Sound	15	27	13	10
⟶ Machine Sound	2	1	0	4
⟶ Music	11	25	9	6
⟶ Rhythmic Beat	3	2	1	0
⟶ White Noise	0	1	3	0
→ Fabric	6	3	4	5
→ Fidget Object	6	10	6	8
⟶ Phone	1	2	1	0
⟶ Ball	3	1	0	0
→ Mug	4	1	11	0
→ Metal	1	1	1	0
→ Chair	1	0	1	0
Human	18	20	27	33
→ Breathing	1	0	0	2
→ Heartbeat	2	0	2	4
→ Own Body	3	1	2	2
⟶ Hand	0	0	2	1
⟶ Arm	2	0	0	0
→ Human Touch **	11	11	15	23
⟶ Hand	8	8	11	10
⟶ Hug	1	0	4	6
⟶ Partner	2	1	0	11
⟶ Shoulders	1	3	2	1
⟶ Skinship	1	4	9	13
→ Human Voice **	1	7	9	2
⟶ Conversation	1	6	7	1

Code	**Interview**	**Bar**	**Cafe**	**Home**
Natural	31	9	10	15
→ Animal *	14	5	4	12
⟶ Animal Sounds	7	1	0	5
Birdsong	4	0	0	2
Purring	3	1	0	3
⟶ Animal Touch	7	4	4	7
Cat	6	2	3	6
Dog	1	0	2	1
→ Forest Sounds	0	0	2	0
→ Water	13	3	2	2
⟶ Rain	4	1	1	0
⟶ Waves	5	1	0	1
→ Wind	3	0	1	1
Social	26	23	25	35
→ Animal *	10	5	4	10
⟶ Animal Sounds	3	1	0	3
Purring	3	1	0	3
⟶ Animal Touch	7	4	4	7
Cat	6	2	3	6
Dog	1	0	2	1
→ Human Touch **	11	11	15	23
⟶ Hand	8	8	11	10
⟶ Hug	1	0	4	6
⟶ Partner	2	1	0	11
⟶ Shoulders	1	3	2	1
⟶ Skinship	1	4	9	13
→ Human Voice **	1	7	9	2
⟶ Conversation	1	6	7	1

Table 4.3: Codes defined for social scenario responses. Note that this does not include codes considered to be attributes, i.e., describing the properties of an experience (e.g., warmth, pressure). *Some Animal codes were classified as both Social and Natural. **Human Touch and Voice were classified as both Social and Human.

Background Sound		**Pressure**		**Repetition**		**Soft**		**Warm**		**Stroking**	
Music	51	Hug	10	Heartbeat	8	Fabric	13	Mug	19	Animal Touch	10
Human Voice	15	Hand	6	Rhythmic Sound	7	Animal Touch	7	Animal Touch	9	Skinship	3
Machine Sound	7	Back	5	Vibration	3	Music	2	Partner	9	Fabric	1
Waves	6	Shoulders	2	Ticking	2	Human Voice	1	Hand	2		
Rain	6			Machine Sound	1	Hand	1	Fabric	2		
Birdsong	6			Tapping	1						
White Noise	4										
Ticking	3										
Forest Sounds	2										

Table 4.4: Number of times attribute codes assigned to different sensations in total across all four social scenarios.

Nature experiences were second most prevalent theme (30), most often suggested as experiences with animals such as *Animal Sounds* (7) e.g., "listening to birdsong", "cat's meow" and *Animal Touch* (7) e.g., "stroking cat fur". Suggestions for *Animal Touch* mentioned *Stroking* and *Soft*ness, attribute codes which also appeared alongside *Fabric*. The natural sounds of *Water* (13), such as rain or waves, was also a prevalent code.

> "The sound of running water whether that's rain, a waterfall or the sea they all help me to relax."

Responses also showed desire for calming *Social* experiences, e.g., with pets (*Animal*: 14) or other people (*Human Touch*: 11). *Hand* was the most common *Human Touch* suggestion e.g., "Holding the hand of a loved one". A total of six other *Human* experiences were suggested, including "the sound of a low heartbeat" and "my partner's up and down breathing movement". One participant suggested a sensation which emulates a real world human experience artificially, "A pulsing vibration to the rhythm of resting heart beat", in a similar manner to the emotionally resonant vibrations developed in this project, or utilised by prior work [11, 38]. The most prevalent attributes codes assigned to suggestions in this scenario were *Background Sound* (25), *Soft* (10), *Warm* (9) and *Repetition* (8).

Bar Scenario (Public, Not Intimate)

In this scenario, we asked participants to envision themselves in an unfamiliar social group in a bar, representing a public and not intimate setting (see Figure 4.5). Responses to this scenario revealed a trend set to continue, when asked to suggest stimuli for a setting participants often made diagetic suggestions, i.e., suggestions which could naturally occur in those settings. The largest experience theme was *Artificial* experiences, encompassing 42 suggestions, most commonly for *Music* (25) as many people suggested they would like to hear "favourite" or "familiar" music playing in the background of bar.

Sixteen artificial tactile experiences were suggested. *Fidget Objects* were suggested 10 times and included both diagetic options like "fidgeting with my keys or watch" or "I would probably play with my phone in this scenario", but also suggestions like "knobbly rubber ball" and "play dough". *Fabric* was suggested three times, as was holding a *Cup/Mug*.

In contrast to the job interview setting, *Natural* experiences were only used suggested 9 times, perhaps because these were incongruous with this setting. Four of these suggestions were *Animal Touch* sensations which could occur in a bar setting, while *Water* (3) and *Animal* (1) sounds were rarely suggested.

Social and *Human* experiences were frequently suggested (23 and 20 times, respectively). *Human Touch* (11) often specified touch from the *Hand* (8) including suggestions of "a hand of my friend on my back" or "a reassuring hand on my shoulder". *Human Voice* (7) was also

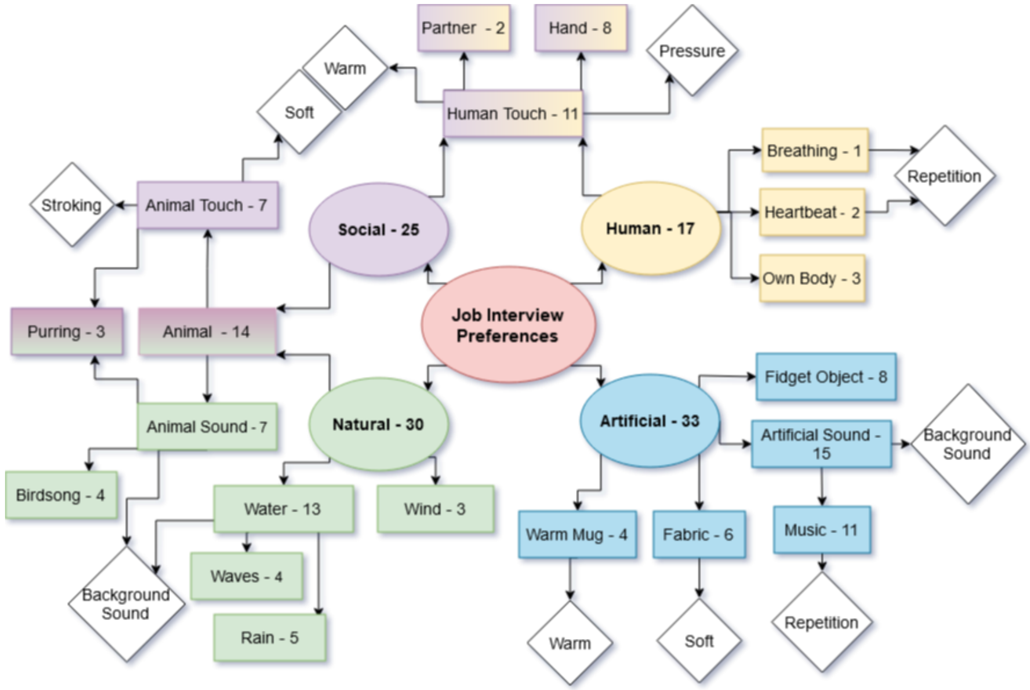


Figure 4.4: Thematic map demonstrating the themes and codes assigned to participant suggestions for calming haptic and auditory sensations during an imagined private and non-intimate job interview setting.

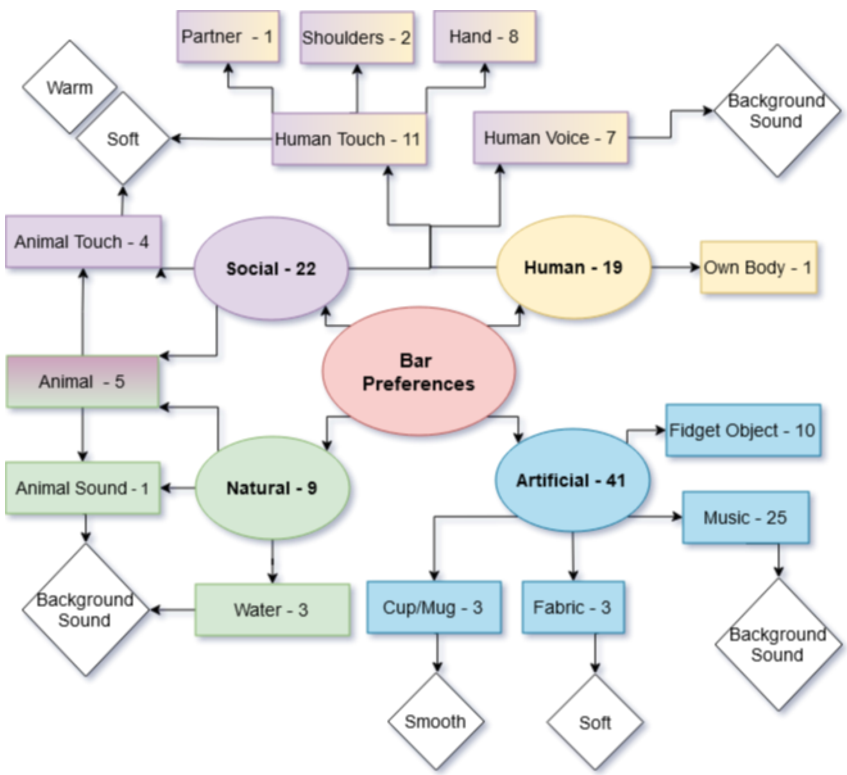


Figure 4.5: Thematic map demonstrating the themes and codes assigned to participant suggestions for calming haptic and auditory sensations during an imagined public and non-intimate bar setting.

common, either as diegetic *Background Sound* such as “background chatter” or from a specific person such as “my mum’s voice reassuring me”.

Cafe Scenario (Public, Intimate)

In this scenario, we asked participants to imagine themselves in a conversation with a friend in a cafe about a serious matter, representing a public and intimate situation (see Figure 4.6). *Social* and *Human* experiences were again prominent here (25 and 27 times, respectively), most often as *Human Touch* (15) suggestions and sub-codes like *Hand* or *Hug*, likely due to the specified intimacy of the scenario. *Human Voice* (9), mostly as background conversation (7) but also as the friend’s voice in the scenario (2), was also suggested. Background conversation and *White Noise* were chosen by some to give the comfort of presumed privacy:

> “Low level conversation so it feels like nobody can hear what we are talking about.”

Artificial experiences were suggested 36 times. *Music* was suggested 9 times, which was often specified as “soft” and “relaxing”. Touch interaction with ‘Fidget Objects’ (6) and ‘Fabric’ (4) were less prominent in this scenario as more participants suggested the diagetic *Warm Mug* (11). Natural experiences were only suggested 10 times, the largest code of which was Animal Touch, with 4 participants suggestions stroking or touching a cat.

Home Scenario (Private, Intimate)

In this scenario, we asked participants to imagine themselves having a one-to-one conversation at home with a partner about their relationship, a socially intimate and private situation (see 4.7). *Human* (33) and *Social* (35) experiences were the most common high level codes in this scenario. The most prominent code was *Human Touch* (23), often specifying “hand holding” or touch from their partner’s hand. These interactions were commonly described with the *Warm*, *Soft* and *Pressure* attributes. *Animal Touch* was mentioned 7 times, typically specified with the attribute *Stroking*, which was a similar prominence to other scenarios despite the home being the setting with the most access to pets.

Natural experiences (15) were more suggested here than in either public scenario, as both Animal Touch and as natural *Background Sound* like “birds singing” and “‘waves crashing”. Artificial experiences were least common in this scenario (23). Fabrics were mentioned 5 times, with attributes ‘Soft’ and ‘Warm’. ‘Fidget Objects’ (8) were often vaguely defined without an object (“Something to fidget with”) or with a variety of options given, such as play dough or stress balls. Only 6 suggestions for made for *Music* and *Background Sound* was least prominent in this scenario, appearing 17 times, primarily as *Music*, *Nature* and *Machine Sounds* (e.g. “traffic”).

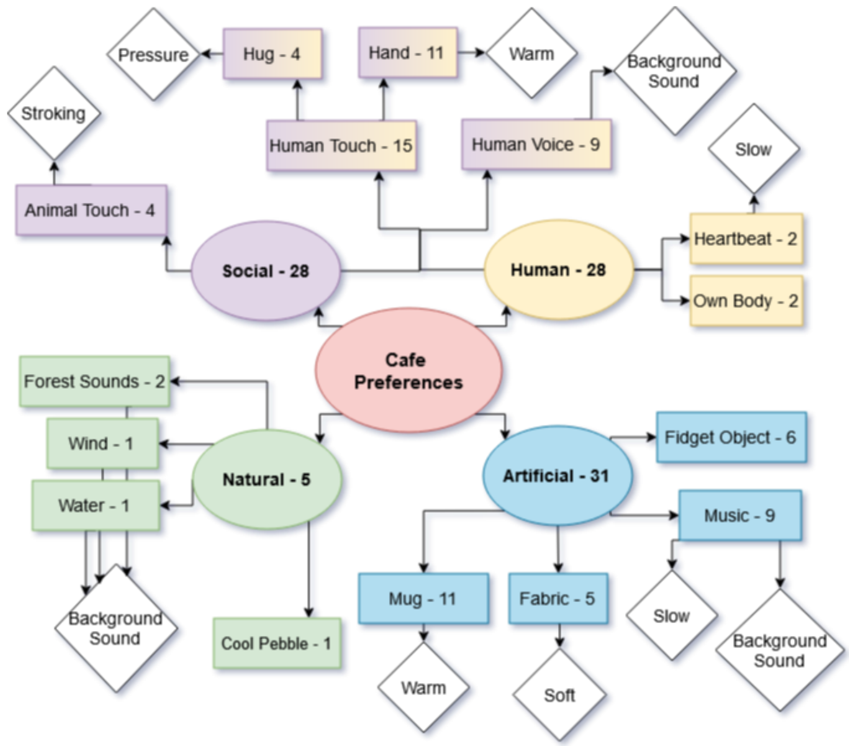


Figure 4.6: Thematic map demonstrating the themes and codes assigned to participant suggestions for calming haptic and auditory sensations during an imagined public and intimate cafe interview setting.

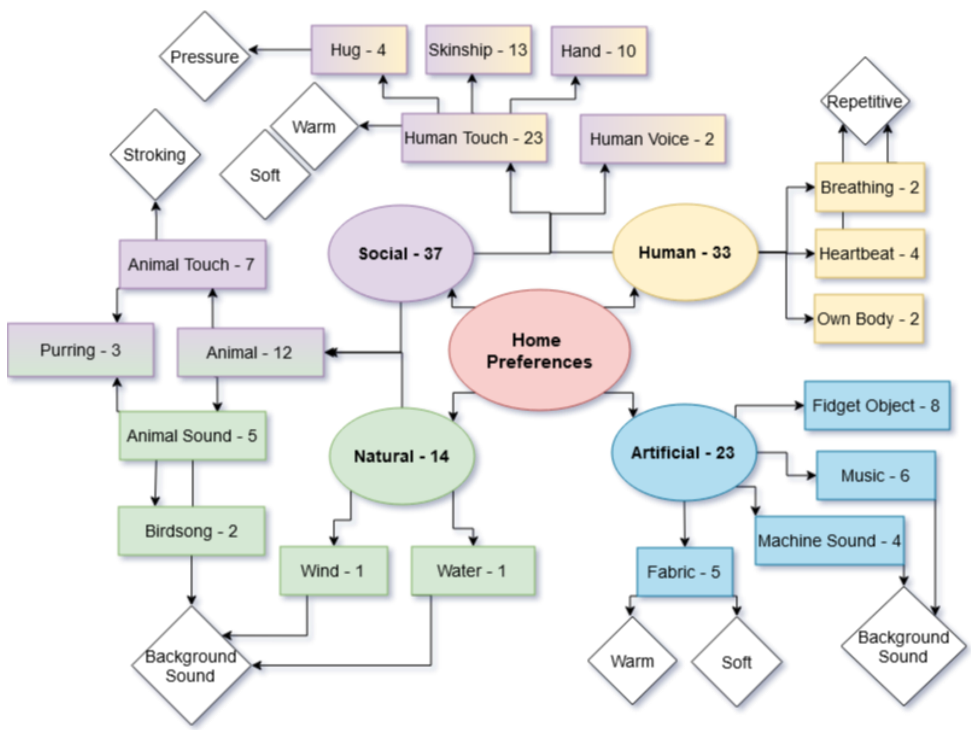


Figure 4.7: Thematic map demonstrating the themes and codes assigned to participant suggestions for calming haptic and auditory sensations during an imagined private and intimate home setting.

Predefined Stimuli Preferences

After making a suggestion for each scenario, participants were given a selection of stimuli hypothesised as calming options, drawn from Experiment 2 and pilot test suggestions. This selection and the number of times in total each stimulus was chosen can be seen in Table 4.5. Some types of calming experience were much more prominent when picked from a selection then suggested. *Natural* experiences were the most prevalent theme in stimuli selection, with *Rain*, *Crashing Waves*, *Running Water* and *Wind* selected a combined 354 times. Stimuli grouped as *Artificial* experiences: *Hairdryer*, *Vacuum Cleaner*, *Keyboard Clicks*, *Engine Idling*, *Holding Warm Mug* and *Fidgeting with Object* had 247 selections. *Slow Heartbeat*, *Slow Breathing* match the *Own Body* code, selected 171 times. *Human* and *Social* sensations such as *Skin Stroking*, *Muffled Conversation*, *Footsteps*, *Scratching* and *Brushing*, had 167 selections. The disparity between theme prominence when comparing suggestions to selections may indicate that, while participants suggested stimuli that were diegetic for each scenario, they considered a wider selection of stimuli potentially calming when prompted with more possibilities.

Stimuli	n	Stimuli	n	Stimuli	n
Holding Warm Mug	169	Slow Breathing	74	Footsteps	12
Rain	142	Running Water	73	Engine Idling	11
Cat Purring	106	Wind	64	Keyboard Clicks	9
Slow Heartbeat	97	Fidgeting w. Object	55	Vacuum Cleaner	6
Skin Stroking	79	Muffled Conversation	49	Scratching	5
Crashing Waves	75	Brushing	22	Hairdryer	3

Table 4.5: Eighteen pre-selected stimuli that respondents could indicate preference for, ordered by total number of selections (n).

To establish if the stimuli selected were significantly affected by social scenario, Chi-squared tests were conducted for the nine most selected stimuli, avoiding stimuli with smaller selection counts, for which statistical significance would be hard to ascertain. Bonferroni correction indicated an alpha of 0.0056. Three stimuli were significantly more common in the Job Interview than in other scenarios ($p < 0.0056$): *Running Water* ($\chi^2(3) = 15.1$), *Crashing Waves* ($\chi^2(3) = 22.4$) and *Rain* ($\chi^2(3) = 14.2$), supporting qualitative findings from the interview scenario where natural stimuli were more prevalent in the interview scenario. All three were water related, suggesting water phenomena may be particularly preferred among natural experiences. Social anxiety status (whether the participant scored 34 or higher on the SIAS) had no effect on stimuli selection below the corrected alpha.

Significant effects of age were investigated with one ANOVA for each of the nine stimuli, while significant effects of gender were investigated using one Chi-squared test for each stimulus. For gender, men more often selected (p<0.00056) *Heartbeat* ($\chi^2(3) = 16.2$), while women more often selected ($p < 0.0056$) *Warm Mug* ($\chi^2(3) = 20.1$), and *Fidgeting* ($\chi^2(3) = 25.0$). Regarding age, participants under the median age of 34 more often selected ($p < 0.0056$) *Warm*

Mug, *Skin Stroking*, *Wind*, *Fidgeting* and *Rain*. Participants aged 34 and over more often selected ($p<0.00056$) *Cat Purring*, *Heartbeat* and *Running Water*.

Texture Preferences

After suggesting and selecting calming sensations in the four imagined social scenarios, participants were asked to indicate one or more textures they found generally pleasant to touch, irrespective of scenario. This would inform the texture selections offered to co-design participants later. Four high level codes for texture preferences were created: *Soft* (45), *Smooth* (15), *Fabric* (44) and *Hard* (18). Each of these high level codes were assigned more specific subcodes. From 81 total responses there were 32 texture codes in total. *Soft* comprised of *Animal* textures (11), *Fabrics* (26) and 8 unspecified. *Smooth* and *Hard* codes were specified with natural materials such as *Wood* (11) or *Stone* (12), and 6 mentions each of artificial materials like *Metal*, *Ceramic* and *Plastic*. *Fabric* comprised 9 different varieties, the three most popular being *Velvet* (13), *Fur* (12) and *Bedding* (9). This wide array of textures prompted the inclusion of many different textures included as building materials in later prototyping, such as soft fabric, *faux* fur, plastic and metallic materials.

Fidgeting Preferences

Participants were then asked to write about one or more objects they fidget with when stressed, to inform which materials or form factors should be provided in later prototyping sessions. Two high-level codes were assigned to the responses: *Own Body* (35) and *Artificial Objects* (56). Within *Own Body*, responses cited fidgeting with *Hair* (14), *Fingers* (9), *Fingernails* (7) and *Hands* (5). More relevant to future prototyping were the prevalent responses in the Artificial objects code: *Phone* (25), *Pen* (20), *Paper* (8), *Fabric* (8), *Fidget/Stress Toy* (7) and *Jewellery* (6). Considering the two most prominent choices, while pens may be too small to augment with a Haptuator, this finding motivated the inclusion of a phone case for participatory prototyping.

4.3.6 Discussion

Hypotheses

Survey 2 elicited preferences for calming sensations from users in different imagined social scenarios, informing which new emotionally resonant vibrotactile stimuli to present in future experiments and corroborating the future use of existing stimuli. It also elicited preferences for texture and stress-relieving fidget objects, to inform the materials provided during later participatory prototyping. While this was primarily an exploratory study, there were some hypothesised outcomes based on results of prior studies in this thesis.

It was first hypothesised that respondents would prefer social touch in private and intimate scenarios, as this was found in Survey 1. While *Human Touch* experiences were suggested 11 times or more in each scenario, they was most prominent in the private and intimate Home scenario, suggested 23 times. The second highest rate of suggestions for *Human Touch* sensations was for the public and intimate cafe scenario, where they was suggested 15 times. These results support this hypothesis. Both prior work and this project have not found an effective method of emulating social touch with single-actuator vibrations, making this preference hard to capitalise upon. As a sensation preferred in private and intimate situations, however, it is also less of a priority as public settings are more relevant for social exposure intervention, due to the higher levels of perceived scrutiny from strangers.

The second hypothesis predicted that suggestions and selections for animal touch would be more prevalent than human touch, as this was suggested by the findings of Survey 1. For suggestions this did not bear out. In total, suggestions were coded as *Animal Touch* 22 times, while *Human Touch* suggestions were made 60 times. User anxieties of being observed and showing intimacy publicly may have applied less to the respondents of this survey, as the majority of respondents were not socially anxious, whereas in Survey 1 only socially anxious responses were considered. Social anxiety had no significant effect on any pre-selected stimuli, including *Human Touch* stimuli like *Skin Stroking* and *Slow Heartbeat*, however, indicating this may not have impacted the results. Additionally, as all of the scenarios in this survey directly imply the presence of other humans as part of the illustrated social scenario, this may bring to mind human touch when suggestions are being made. The outcome for stimuli selections was different. *Cat Purring* was selected 106 times in total, whereas *Skin Stroking* was selected 79 times. As both of these sensations are more specific than general *Animal Touch* or *Human Touch*, however, it is hard to directly relate this to the hypothesis. It does show that participants were happy to endorse *Cat Purring* as a calming sensation when prompted, even if far fewer offered it as their preferred or primary suggestion.

Impact of Scenario

The primary purpose of this survey was to understand the breadth of user preferences for calming sensations and whether they depended on social setting, to best inform the set of stimuli, textures and form factors offered to users when allowing them to personalise a haptic intervention object in later studies. Participants showed a strong bias toward diegetic suggestions in each scenario; e.g., *Music* was most prominent in the Bar scenario, and *Holding a Warm Mug* for the Cafe scenario. The Job Interview was the exception. Perhaps because there are few diegetic pleasant stimuli present in a such a scenario, participants more often suggested and selected suggested stimuli they may have found generically pleasant, such as natural sounds. This bias for diagesis was less pronounced when selecting stimuli, however, indicating that, while the scenario was influential in prompting participants, it did not limit the variety of sensations they felt could be calming when presented with the pre-selected set. Given this, future studies adopted the approach of presenting a set of stimuli for participants to choose from, but the contents of that set would be drawn from an evaluation of a wider set of emotionally resonant stimuli, informed by suggestions and selections made in this survey.

Impact on the Stimuli Presented in Experiments

Of the eight stimuli used in Experiment 2, only *Rustling Leaves* was never suggested by participants. *Cat Purring* and *Heartbeat* were both selected over 90 times and suggestions which mentioned cats and heartbeats were made in all 4 scenarios, supporting the past and future inclusion of these stimuli. *Slow Breathing* was selected 74 times and suggested 3 times while Muffled Conversation was selected 49 times but background human voices were suggested 16 times, motivating the inclusion of both these stimuli in the set. Natural water sounds were suggested 18 times and selected 290 times, reinforcing the inclusion of *Small Stream*, *Underwater Bubbles* and *Crashing Waves* and the addition of the *Raindrops* for Experiment 3, which was the most prominent water sensation both suggested and selected.

Other new sensations were added to the emotionally resonant stimuli set in Experiment 3 following the results of Survey 2. While they received only a small number of suggestions and selections, *Brushing*, *Scratching*, *Car Engine* and *Vacuum Cleaner* were trialed in Experiment 3 to see if they could evoke *Human Touch* and *Artificial Sound* experiences, which were otherwise very difficult to represent using vibrotactile stimuli. *Holding a Warm Mug* was the most selected sensation, was suggested 19 times across several scenarios and 41 suggestions were assigned the *Warm* code. The prominence of this theme motivated the investigation of thermal feedback during Experiment 3.

Contribution to Research Question 3

Survey 2 provided first-of-its kind insight into the calming sensations users wish to experience in a variety of potentially socially anxious settings. Along with Survey 1, it directly addressed Research Question 3: *Which calming real-world experiences would users prefer emotionally resonant vibrotactile stimuli to evoke and what factors impact their use in social settings?* As expected from the results of Experiment 2, participants exhibited a wide range of preferences. When suggesting stimuli it was clear the imagined social scenarios influenced the sensations they felt were appropriate or brought to mind calming experiences they had in similar scenarios. When selecting from a pre-defined set, however, it was also clear participants were choosing non-diagetic sensations as calming, suggesting that the external factor of social setting does not necessarily restrict which stimuli are desirable.

Many of the prominent experience themes found via thematic analysis of responses were already represented by one or more stimuli in the set use in Experiment 2. Where possible prominent experiences and sensations which were not represented in Experiment 2 were implemented as new emotionally resonant vibrations, which were then tested in Experiment 3.

Texture and fidget object preferences would also directly motivate the inclusion of building materials provided during later participatory prototyping.

4.4 Chapter 4 Discussion

Chapter 4 directly explored both the experiences and requirements of socially anxious users and the breadth of possible preferences for calming sensations which emotionally resonant vibrotactile stimuli could aim to emulate. Answering questions specific to the needs of socially anxious users was crucial to correctly shaping the path of discovery described in Chapter 5 as the project sought to synthesize the needs of users and the potential of emotionally resonant vibrations into a new social anxiety intervention.

Survey 1 provided primary-source understanding of how socially anxious users currently regulate their emotion in social situations and how they currently experience affective touch, informing whether there is a need for an affective haptic intervention and how it might best be implemented. When asked about their use of safety behaviours to regulate emotion during stressful situations, participants indicated that the behaviours they most often used were were either not calming or prevented them directly engaging in social interaction, highlighting the potential benefit of a calming haptic intervention which could be used mid-conversation. Questions about recent experiences with affective touch suggested that the fear of judgment or observation by others curtailed the applicability of affective touch as a calming intervention for socially anxious users. A vibrotactile intervention capable of affective touch could discreetly re-enable this calming sensation to users.

Survey 2 was an exploratory study that mapped the breadth of affective haptic and auditory preferences indicated by users who both suggested and selected sensations they felt would be calming in four imagined social settings. Qualitative analysis using open-axial-coding was used to categorise these user preferences as shared codes and higher-level themes to understand prominent trends in the data. Participants suggestions showed bias toward sensations which could naturally occur in each given social scenario, however when choosing stimuli from a preselected set, this bias was less pronounced, suggesting users do not specifically require stimuli to be diagetic to preferable or calming. Participants suggested and selected a wide range of sensations. Several of these sensations were already represented in the emotionally resonant vibrotactile stimuli set used in Experiment 2, further motivating their inclusion, while new stimuli were added to the set used in Experiment 3 to better represent the range of preferences found in Survey 2. Survey 2 also elicited user preferences for textures and fidget objects they find calming or pleasant, informing the range of construction materials made available during later participatory prototyping..

4.5 Conclusions and Research Question 3

By answering Research Question 3, this chapter further motivated and specified the use of emotionally resonant vibrations as a social anxiety intervention with a mandate provided by directly observed user preferences.

Research Question 3: Which calming real-world experiences would users prefer emotionally resonant vibrotactile stimuli to evoke and what factors impact their use in social settings?

Qualitative analysis of Survey 2's results allowed user preferences for potential calming emotionally resonant haptic vibrations to be mapped. While user suggestions were influenced by different imagined social scenarios, user selections varied less between scenarios, suggesting that user preferences may be influenced by scenario but were not scenario-prescriptive. The results of Survey 1 suggested another factor will increase user preference for calming touch interactions: avoiding observation of touch by others. It also suggested that, among social touch experiences, users prefer sharing touch with an animal or a romantic partner, to sharing touch with a friend or family member. Emotionally resonant vibrotactile stimuli have the potential to meet or emulate these three requirements and, by leveraging knowledge of the breadth of user affective preferences found in Survey 2, can potentially provide calming haptic feedback to a wide array of users.

Chapter 4 detailed two surveys which observed how socially anxious users experienced safety behaviours and social affective touch, and user preferences for calming sensations. This provided motivation for developing emotionally resonant vibrations as a novel social anxiety intervention and which haptic sensations to include in future experiments. The last two experiments discussed in Chapter 5 put the proposed intervention into the hands of socially anxious users. In the following Prototyping sessions, socially anxious users engaged in participatory prototyping to produce personalised objects to house emotionally resonant vibrations and provided first-hand feedback on the intervention. The results of this were then used to produce a series of higher-fidelity prototype objects, allowing users to personalise the form factor, texture and vibration of their intervention. The intervention was then evaluated in Experiment 4.

Chapter 5

Emotionally Resonant Vibrotactile Comfort Objects

5.1 Introduction

The previous chapters developed a novel category of emotionally resonant vibrotactile stimuli, motivated and informed by two surveys and trialled over a series of three experiments. These emotionally resonant stimuli were designed to elicit a calming emotional state by reminding users of pleasant past experiences and Research Question 4 asked if discreetly presenting socially anxious users with these stimuli could make it easier for them to engage in face-to-face social exposure:

RQ4: Can emotionally resonant vibrotactile stimuli calm socially anxious users during social exposure?

Chapter 5 takes the final steps to answer RQ4 with two experiments which optimise and assess the use of these stimuli by putting them into the hands of socially anxious users. In the first experiment, a series of participatory prototyping sessions were conducted to address the unanswered question of how the stimuli should be housed and presented, while eliciting applicability feedback from target users. The second and final experiment conducted a psychological and physiological evaluation of the impact of a personalisable emotionally resonant vibrotactile intervention during a social anxiety performance task between a treatment and control group.

5.2 Haptic Comfort Object Participatory Prototyping with Socially Anxious Participants

The primary purpose of this participatory prototyping step was to address the final undefined aspect of presenting emotionally resonant vibrations: what are the specifications of the holdable object that houses the vibrotactile actuator through which the stimuli are conveyed and how do they vary between individuals. This issue was investigated by conducting participatory prototyping, allowing socially anxious users to create objects that suited them, augmenting those prototypes with vibration and eliciting feedback. Prototype trends informed a range of higher-fidelity objects offered to participants of the final evaluation in Experiment 4.

5.2.1 Methodology

This was an exploratory interview and participatory prototyping study which observed participant preferences for form factor and texture when personalising vibrotactile comfort objects. Interviews also allowed their preferences and priorities to be contextualised within their lived-experiences of social anxiety, informing if and how these objects are likely to be used in practise. Comfort objects are objects with which the user has a relationship, providing comfort and emotional regulation through interaction, including tactile interaction [6,33]. While most commonly used by children, comfort objects are also used by adults [33]. The aim of both experiments in Chapter 5 was to leverage personalisation and emotionally resonant vibrations to create calming comfort objects which socially anxious users could use for emotion regulation during conversation.

This experiment utilised participatory design in the development of vibrotactile comfort objects prototypes. Participatory design is a practice of involving end-users in the design process of system or artifact. While it originated as a workplace practise [192], it has since been applied to many fields, including HCI. Participatory design is invaluable in fostering empathy by bridging the gulf of experience between designer and user [30, 126, 202], allowing the consideration and development of designs better suited to their needs. For example Flobak *et al.* conducted a participatory prototyping workshop with a group of fifteen adolescents to develop a virtual reality exposure therapy scenarios for public speaking anxiety [64]. The lived experiences of the participants were used to inform the design of authentic scenarios. The participatory prototyping procedure used in this experiment was modelled after one proposed by Simm *et al.* in their paper *Anxiety and Autism : Towards Personalized Digital Health* [202]. The authors describe providing participants with a small kit of potential components, from which they could construct wearable life-loggers suited to their own aesthetic and tactile preferences (see Figure 5.1). This approach could allow the interventions developed in both Simm *et al.*'s work and this thesis to adapt to the breadth of preferences and requirements shown by end-users. Utilising a participatory design approach, along with semi-structured interviews, allowed both for comfort object designs to be driven by end-user agency and for better understanding of if and how these devices would be applicable to users' personal experiences with social anxiety.

This experiment had three hypotheses grounded in findings from prior studies:

H1: Every stimulus and material would be utilised by at least one participant;

H2: Soft textures and the phone case would be commonly used components in prototyping;

Figure 5.1: A small kit of components which could be provided to participants, proposed by Simm *et al.*'s participatory prototyping study for producing personalised wearable life-loggers (extracted from [202]).

H3: Participants would find their comfort objects calming and pleasant to hold.

Hypothesis 1 was drawn from the breadth of user preferences found in Experiments 2 and 3 and Survey 2. If correct, it would further motivate the decision to pursue a personalisable intervention. The second hypothesis was grounded in the prominence of user preferences for soft textures and phone interactions found in Surveys 1 and 2. Hypothesis 3 follows the finding from Chapter 3 that each participant found at least one stimulus pleasant or calming and thus, by provided participants in this experiment with the ability to choose their preferred vibration and customise a comfort object, each participant would end up with a haptic comfort object they found pleasant and calming. Finally, while this experiment would not directly address Research Question 4 by formally evaluating the comfort object prototypes in a controlled social exposure task, it did prompt users to give initial feedback on how useful they felt their personal prototype could be used during social exposure.

5.2.2 Apparatus

To construct their personal comfort object prototype, each participant was presented with an identical assortment of building materials and tools. The materials offered were chosen to be simple and functional to cut and shape, while also being based on trends identified in respondent preferences during Surveys 1 and 2. Lego and play dough were provided to allow participants to construct variable shapes and structures, while also fulfilling the want for *Soft* and *Hard* textures respectively. Additionally, a phone case was provided as a structure, as participants in Survey 1 and 2 expressed preference for holding or focusing on their phones during stressful situations.

To accommodate the preferences for *Soft* and *Fabric* textures, the most prominent themes identified in Survey 2, sheets of soft felt and faux fur were provided. The preference for *Smooth*,

Figure 5.2: The set of building materials and textures provided to each participant for participatory prototyping a comfort object.

Plastic and *Metallic* textures was fulfilled by providing sheets of foam and roll of both plastic film and tin foil. Finally, a sheet of sandpaper was provided as singular rough texture option, although it was not expected to be as utilised as often as other materials, given prior study results. Participants were provided with scissors, sticking tape and Blu Tack to cut, shape and stick materials together as wanted. As in prior studies, a Haptuator Mk II [A.1] was used to convey the emotionally resonant vibrations and was attached to each prototype with tack, tape or inserted into the play dough in an *ad hoc* fashion, depending on each prototype's shape and how the participant indicated they meant to hold their object.

5.2.3 Participants

Twenty participants (six male, ten female, four non-binary) were recruited using university, email and social media channels. Mean participant age was 26.2 (σ = 3.76). Participants were recruited if they were at least 18 years old, had full haptic perception in their hands and scored 34 or above on the SIAS [A.4] (sent via email to those who requested participation), indicating likely social anxiety.

Participant	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20
Age	32	23	24	32	28	34	25	26	25	25	24	31	21	20	28	n/a	24	29	n/a	n/a
Gender	M	M	F	NB	NB	M	M	M	F	F	F	M	F	F	F	F	F	F	NB	NB

Table 5.1: Ages and genders given by participants who took part in participatory prototyping. Three participants refused to have a specific age recorded in data. M = male, F = female, NB = non-binary.

5.2.4 Procedure

The experiment took place inside a large office space with only the participant and researcher present, both wearing personal protective equipment (PPE), to reduce the risk of contamination during the COVID-19 pandemic. Participants read an information sheet [B.6.1] before signing a consent form [B.6.2] to proceed with the experiment. The experiment took approximately one hour to complete and participants were paid with a £10 Amazon voucher for their time.

The experiment was comprised of three sections. The first was a semi-structured exploratory interview with the participant to understand their current lived experiences with social anxiety and how they manage it. Participants voices were recorded during interviews. These recordings were then transcribed and anonymised. Each participant was asked the following three questions and open-ended discussion was promoted in the answering of each one:

1. *How has social anxiety or shyness manifested or impacted you in social situations?*
2. *Do you currently use something to make social situations easier, like a distraction or mental technique?*
3. *Have you found any kinds of touch with an object, animal or person calming during social situations?*

In the second section participants prototyped a comfort object that they felt would be calming to hold. They were given building materials designed to allow them a variety of form factors and textures, as informed by user preferences in Survey 2 (see Section 4.3). Participants were given a flexible timescale to build their object and, on average, took approximately ten minutes. After their object was built, the researcher augmented the participant's design with the Haptuator, creating an impromptu emotionally resonant vibrotactile comfort object.

In the final section, participants were asked to hold their prototype while experiencing each of the nine emotionally resonant vibrations retained following Experiment 3, *Cat Purr*, *Heartbeat*, *Crashing Waves*, *Rain*, *Small Stream*, *Car Engine*, *Slow Breathing*, *Brushing* and *Underwater Bubbles*. Participants gave feedback on each stimulus and were then asked to choose one or more of them as their favourite. With a favourite combination of stimulus and object chosen, participants were asked three more questions in a semi-structured interview:

1. *What was your intent in creating this object?*
2. *How does the prototype compare to your intent?*
3. *How does the addition of vibrotactile stimulation change your perception of the object?*

This was followed by a final structured post-session survey [B.6.3] which assessed the participant's experience in the experiment, their sentiment toward their prototype and toward the vibrotactile stimuli. The vibration, shape, texture, materials and a short description and photograph of their object were also recorded.

5.2.5 Results

As in Survey 2, thematic analysis was conducted to analyse qualitative data. As before, coding was conducted in two iterative rounds by two coders for validity. Both researchers coded the entire data set once each initially, before conducting a synthesis meeting to produce one combined code scheme. Both researchers then re-coded the data using this synthesised set of codes, then conducted a second synthesis meeting which resulted in a final set of codes and themes describing the data. To better accommodate this more detailed interview data, the qualitative analysis software nVIVO [1] was used by both coders to create and apply codes and themes. In total, nine themes were identified, comprising a total of 61 codes for concepts which were mentioned by at least two participants (see Figure 5.3).

Experiences with Social Anxiety and Affective Touch

The experiences of socially anxious users provided first-hand context for how emotionally resonant haptic comfort objects could be used by real users and what improvements this intervention could provide when compared to current coping strategies or affective touch experiences. Social avoidance was a common talking point in participant interviews, mentioned by sixteen people. Participants described either staying passive in social scenarios to avoid initiating social contact, or avoiding them entirely.

> P10 - "My friend invited me to meet a bunch of his friends they just had like a flat gathering and I thought it wouldn't be so bad, but I got there and there was just too many people and I just felt scared. So I just went away, (...) just being scared I can't think straight I can't really rationalize or just be like 'oh am I being rude by just leaving them?', I just need to get out."

> P11 - "At one point, when it was really bad, I've stopped taking public transport because being in such close contact with other people and worrying about what they think about me, and what a possibility of interaction with them, was too difficult for me and overall I don't know (...) in any situation that that you can you can think of where you would have people, (...) I'd rather avoid it."

This fear and subsequent avoidance of interaction was also present in video-call environments that participants had experiencing during the COVID-19 pandemic.

> P14 - "I find tutorials very like scary, um, mainly because people don't... a lot of people especially on Zoom don't speak but it kind of feels like everyone's looking at you."

[1] https://www.qsrinternational.com/nvivo-qualitative-data-analysis-software/home

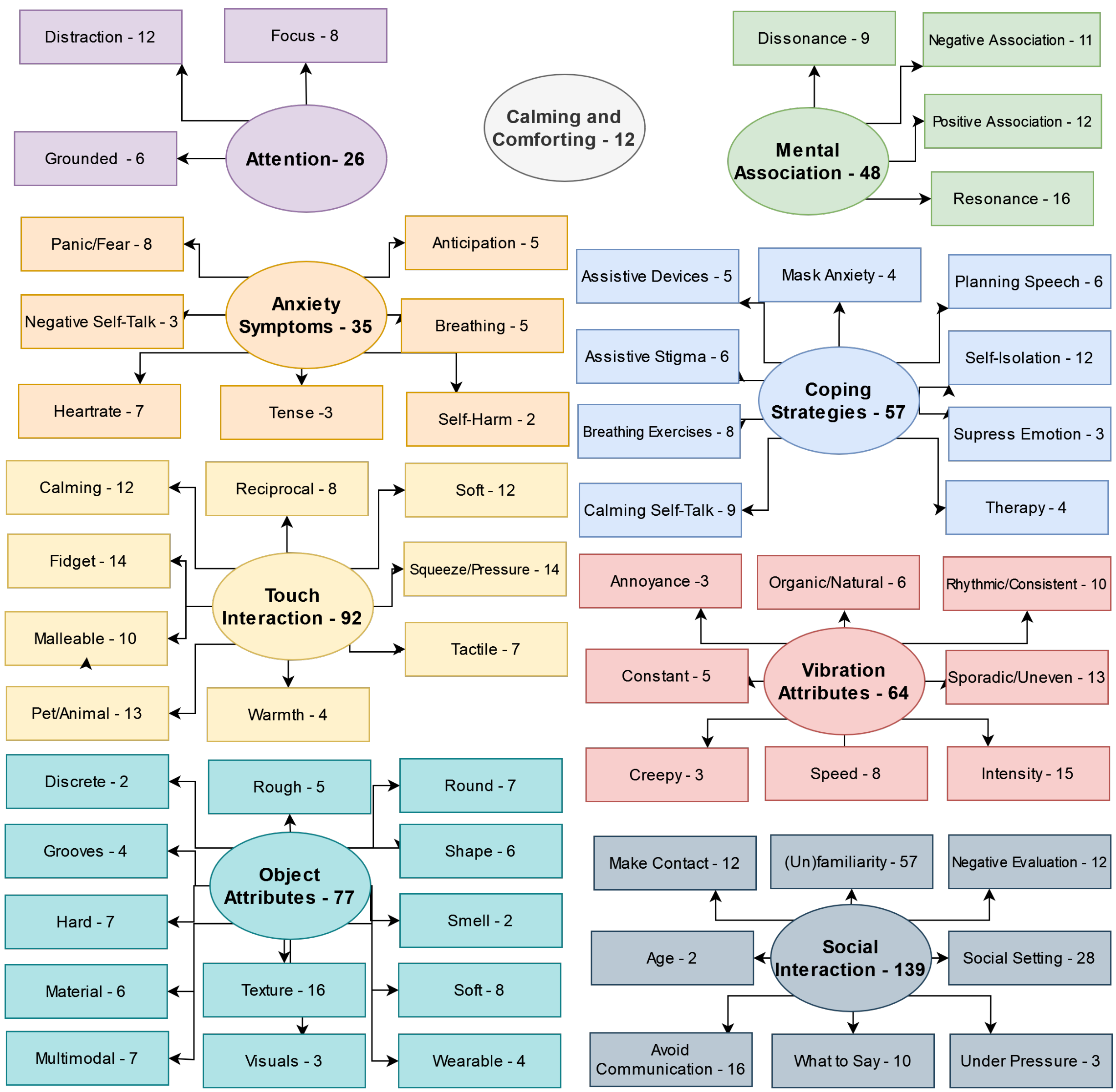


Figure 5.3: Thematic map of the qualitative codes and themes created to represent the data from 20 semi-structured interviews with socially anxious participants who took part in participatory prototyping regarding their experiences with social anxiety and their comfort object prototypes.

> P9 - “Now we have everything on zoom and we have seminars but I cannot talk, I get extremely nervous, my heart beats faster and then my hands get all cold and shivery”

These experiences of avoidance highlight the need for calming interventions which can be used during social interaction, like the one suggested in this work, as reducing the difficulty of facing one’s fears should allow more users to take part in social exposure, a vital part of all core therapies for social anxiety.

Participants mentioned various physiological and psychological symptoms they experienced due to social anxiety which could be alleviated with emotional regulation facilitated by a calming haptic intervention. Six participants mentioned being overly aware of their heart-rate or breathing during social situations, while seven others noted other symptoms like tensing up, shivering, nausea and biting or picking at their nails.

> P7 - “I tense up in the back of my legs and sometimes my feet, which can either be painful or inhibits mobility, or I get like a wee bit panicked and can feel my heart racing a wee bit more, or like my breathing gets a little bit funny.”

Twelve participants mentioned pre-occupation with negative social evaluation. This pre-occupation made it harder for them to engage socially and make/keep contact with others. Several specifically mentioned that they weren’t sure how to act ’normal’ or not ’weird’.

> P5 - “I’m always worried that like “oh you can’t say that because that’s just really weird” and i find myself like over overthinking what I’m gonna say. you know like trying to pretend to be normal. somehow it just doesn’t... i don’t know what to do.”

Cognitive modelling of social anxiety (see Section 2.2.1) predicts that when participants observe these symptoms it can worsen their anxiety, causing a negative feedback loop. This research posits that providing an external calming haptic sensation to focus on instead of these interoceptive symptoms could stall this feedback loop and prevent worsening anxiety.

Familiarity with people or objects played a role in participant attendance of social events. As expected, anxiety or fear of interacting with unfamiliar people was one of the most prominent themes, mentioned by 15 out of 20 participants. This can cause people to lose access to practical and leisure spaces, as described by P11:

> P11 - “I’ve stopped taking public transport because [of] being in such close contact with other people and worrying about what they think about me and what a possibility of interaction with them was too difficult for me (...) In any situation that that you can you can think of where you would have people I’d rather avoid it.”

Four participants noted that they felt more comfortable attending or existing in settings with unfamiliar people when with one or more close friends, while five participants reported having used an familiarity assistive device in this manner to calm them, such as distracting themselves with their phone, a plushie, or a fidget-cube. Four highlighted, however, that using these devices in social situations could attract assistive stigma, discouraging their use.

> P4 - “Most of the things that I would take with me to a public setting would be fidget toys. Yes at home I have things like plushies and stuff if I get anxious, but I would be embarrassed to take something like that.”

This highlights the need for discretion when designing a calming intervention for social use, supporting the strengths of vibrotactile stimuli which can be deployed flexibly, invisibly and quietly. The most popular coping mechanism, mentioned by twelve people, was self-isolation, a maladaptive strategy which prevents social exposure.

Finally, participants were asked if they found any kinds of touch calming or comforting. The results were reminiscent of Survey 1 as most prominent was touch with pets or animals, mentioned by ten people, and fidgeting with objects, mentioned by six. Five people mentioned human touch and five others said none.

> P12 - “cats are great for that... because you know they’re you know they’re soft and it’s very socially acceptable to pay attention to a cat.”

> P11 - “I do find touching very soft things and so, for example, plushie things or even very soft fabric clothing very soothing as well I kind of... I don’t know how to scrunch it a little bit and then that is helpful. (...) A hamster that I used to have, which was quite like a furry animal as well (...) that was helpful to calm me down.”

Emotionally resonant vibrations could provide the benefits of animal touch in settings when pets are not accessible and an active haptic element may provide more effective distraction from interoceptive symptoms than passive object touch.

Form Factors

Participants produced a wide array of comfort objects which varied in texture, form factor and their intended meaning for each individual (see Figure 5.4), but some notable trends were observed. Objects were classified by form-factor, the materials used for exterior texture and attributes identified during qualitative analysis (see Table 5.2.5).

Seven participants produced round prototypes, making it the most prominent form-factor. Several cited that they chose a round shape due to how it allowed them to hold the object, e.g.: “it fills the hand”, “something that you could hold, you know like clutch, almost like so you could really apply pressure to it”. Past personal experiences could also be important when choosing a comfort object’s shape, as highlighted by P16 (Participant 16):

Form Factor	n	Texture Materials	n	Attributes	n
Round	7	Play Dough	8	Soft	13
Finger-grooves	5	Fur	8	Multi-textured	10
Square	3	Felt	5	Smooth	9
Model	3	Cling Film	2	Malleable	6
Wearable	2	Lego	3	Rough	5
		Sandpaper	2	Fidgeting	4

Table 5.2: Table showing the prevalence (n) of the different properties of comfort objects produced during participatory prototyping. Form Factor indicates the shape of the objects, Texture Materials describes which materials participants used to give their objects texture and Attributes lists how often qualitative codes were assigned to different objects.

> P16 - "I quite like throwing balls, stress balls and some things. I never really bought a stress ball, [it's] just always given. You know you win a game or something and I quite like playing with and I quite enjoy ball games, so I was like, what if it was just something I could hold like that and, you know, squish and throw, all the rest."

Five participants prototyped comfort objects which features a series of finger grooves. These objects tended to have an elongated shape, allowing the user to hold it like the "grip on (...) some power tools", as noted by P10. These grips were created using Play Dough, allowing them to be moulded by each participants hand, ensuring a fitting grip. Three prototypes were produced with a square-edged shape, with structure provided by Lego. They featured a mix of external textures, with all three participants utilising the inherent smooth and rough Lego textures and the addition of soft felt or fur. P15, who produced "three tactile steps" from Lego, added felt as they felt "well it needs to be soft". Two of these square objects featured fidgeting interactions that involved moving, or detaching and re-attaching components, which one participant likened to the interactions on a fidget-cube. Another prototype was formed in the shape of a spindle and the participant described spinning it between their fingertips to calm themselves.

Fourteen participants highlighted the desire to be able to squeeze, hug or put pressure on their object and designed their object accordingly. P4 and P7 used a Lego core to give their prototype "a harder center so that there's some resistance"(P4) and four participants noted that they wished for their object to emulate the squeezing interaction of a stress ball. Others valued an objects malleability when performing squeezing interactions, engaging in playful interactions. P14 created an object with multiple Play Dough colours contained separated into cling-film compartments, achieving both visual and tactile malleability: "I can squeeze it in ways that like distorts how the colors are seen".

While some prototypes were constructed purely for their pleasant haptic properties, others wished to imbue their object with specific meaning. Objects were modelled after real world concepts like a small doll, a flower and pillow which a participant imagined could be upholstered with fabric from the clothes of a comforting loved one.

> P13 - "I wanted something aesthetics like in the sense that it meant something for me. I can give it give it a name or an identity to comfort me as well and yeah I just wanted something that I can hold yeah hold in my hand"

Textures

The most prominent textures used were soft materials like fur and felt, used 13 times out of the 20 prototypes. A common attribute combination was soft and round prototypes, appearing seven times. Several participants cited an emotional resonance effect as motivation for choosing soft textures:

> P6 - "I wanted to wrap it in this kind of furry sheet because to me it was almost like nurturing a little chick or a bird, you know you hold it in your hand and it's soothing to hold on to and it's relaxing and calming"

> P7 - "I've got a pet cat and the kind of furry one is like most of cat's fur."

While soft textures were most prominent, they often appeared on one side or area of an object featuring multiple textures, allowing the designer a range of tactile experiences. Half of the prototypes features two or more textures, combining soft, smooth or rough textures depending on the participant's intent. P11 created a reversible felt/fur cover for their spherical object, allowing them to choose between the emotionally resonant experience of "touching a pet" or a more general soft experience. Three participants produced objects with soft and rough textures, highlighting that tactile "contrast"(P7, P20) it offered. Others enjoyed the base texture of the Play Dough and Lego building materials but wanted to partially augment them with soft surfaces:

> P12 - "At first I was just like 'oh you know like the two pieces of Lego are like good enough' but I was like oh you know I could have some felt and it would be a bit a bit more pleasing."

This trend highlights that participant preferences for texture should not only be considered in isolation, but how different texture combinations can provide specific tactile experiences.

Emotionally Resonant Stimuli Preferences and Feedback

Every vibration was selected by at least two participants as their preferred emotionally resonant stimulus to augment their prototype (see Table 5.3). *Cat Purring* was most prominent, chosen by half the participants as their favourite/joint-favourite calming stimulus to experience with their comfort object. Six of the prototypes for which *Cat Purring* was selected featured a fur texture and several participants noted this connection: P6 - "that's very nice because it is very accurate", P12 - "P12: okay I definitely like that one. I'm also a big cat fan". As in prior studies,

Figure 5.4: Comfort objects created by socially anxious participants via participatory prototyping from a variety of possible building materials (see Section 5.2.2).

participants could find a stimuli emotionally resonant, but resultant emotions were not always positive. While P7 thought the *Car Engine* "could be quite reassuring and reinforcing", for P4 it brought to mind memories of "being carsick and my parents shouting at each other over directions", and several participants found Heartbeat "creepy", especially went combined with the texture of Play Dough. Thirteen participants specifically mentioned preferring or disliking stimuli based on whether they were constant and regular or sporadic and irregular. P14 commented "I like the car engine and still breathing were like the same reasons that they were both quite chill and consistent" while after experiencing the *Crashing Waves* stimuli P15 said "that's nice. I like the ones that have like a kind of shift, you know so it's not just kind of constant (...) there's like a movement too". These results align with findings from Experiment 2 and 3; the effective emotional resonance of a stimulus varies between people, as does their subsequent emotional response, and some participants formed positive or negative responses for unrelated reasons. By providing a varied set of stimuli, every participant was able to find at least one they preferred.

Stimuli	n	Stimuli	n	Stimuli	n
Cat Purring	10	Brushing	6	Underwater Bubbles	4
Car Engine	6	Crashing Waves	6	Small Stream	2
Slow Breathing	6	Heartbeat	5	Raindrops	2

Table 5.3: Total selections (n) of preferred emotionally resonant vibrotactile stimulus by twenty participants when trialling every stimuli as part of their comfort object prototype, listed from most to least.

Feedback given in the post-session survey further supported the augmentation of comfort objects with emotionally resonant vibrations (see Figure 5.5). Sentiment about the prototypes was largely positive, with 90% of participants finding their vibrotactile prototype pleasant to hold and 70% finding it calming to hold. The most important aspect of the comfort objects was their shape and texture, as indicated by 95% of participants, but 70% felt that the vibration was also an important component. 60% of participants specifically wanted the vibration they chose to match its texture and shape, creating a holistic resonant experience. All this indicates that, while participants did not view the emotionally resonant vibrations as the most crucial aspect of their comfort objects, they were still well received and felt by most to add value to them. 85% of the socially anxious participants felt that a comfort object like their finished vibrotactile prototype could be helpful in an anxious situation, feedback which reinforced the research direction of the project and motivated the following empirical evaluation.

Given the possible distress caused to socially anxious participants due to the one-to-one conversations in this experiment design, they were also asked to give feedback on their participatory prototyping experience. All participants reported that the researcher made them feel comfortable and informed during the sessions, and that they felt their input was valued. 95% found the experience rewarding and satisfying. 15% of participants reported that the participatory design experience made them feel anxious.

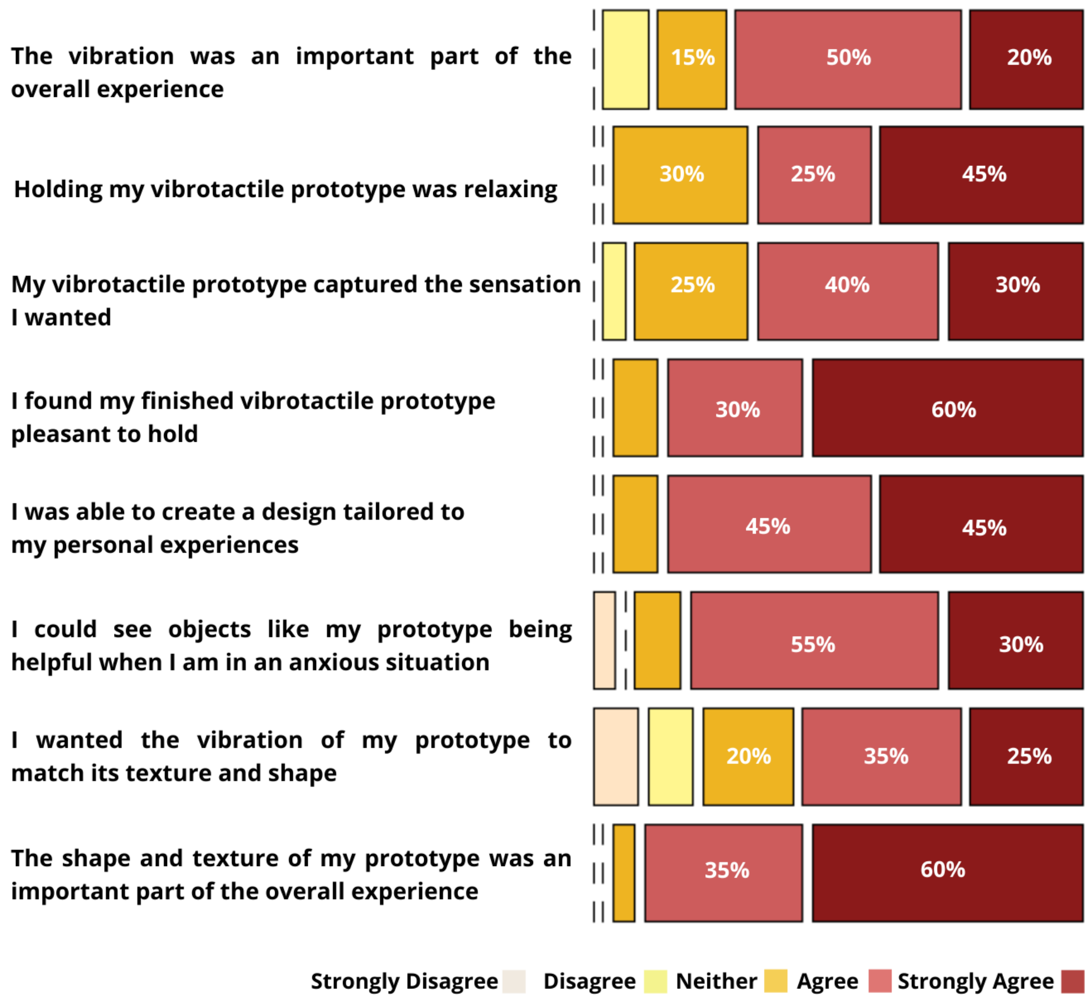


Figure 5.5: Post-prototyping survey results indicating participant sentiment around various aspects of their comfort object.

5.2.6 Discussion

Participatory prototyping of comfort objects with socially anxious users was conducted, to identify prominent trends in preference for form factor and texture, informing higher fidelity prototypes used in Experiment 4. Each prototype was augmented with a Haptuator, then participants experienced each emotionally resonant vibrotactile stimulus, chose a favourite and gave feedback on their experience with their impromptu haptic comfort objects.

The results of this experiment drove the design of a set of higher fidelity prototypes that could encompass the most prominent preferences for form factor and texture. Participants produced a wide variety of prototypes, but common trends were observed between them. Based on these trends, the higher fidelity prototypes in Experiment 4 would be produced in round, grooved and square form-factors. While three participants built models, these were very specific to their personal experiences and so were not informative when designing objects for more general appeal. Texture preferences were broad, so the higher-fidelity prototypes would be feature comfort objects with soft, smooth, malleable and rough textures and one object would feature a multi-textured design, a property which embodied by half the prototypes made during prototyping. Detailed discussion of these higher-fidelity prototypes can be found in Section 5.3.2.

Hypothesis 1 stated that each stimulus and material would be utilised at least once by a participant in their prototype comfort object, drawing on the breadth of user preferences shown in prior studies. Every vibrotactile stimulus was chosen as a favourite or joint-favourite at least twice, with the most popular being *Cat Purring*, a stimulus which allowed many participants to evoke the calming animal touch theme which was identified throughout the experiment and the wider project. Not all materials were used, however, as neither tin foil or the phone case was utilised in any comfort object prototypes. The absence of tin foil was not wholly unexpected as the metallic texture was a minor theme in Survey 2. The lack of prototypes which incorporated the phone case as a base was surprising. It was also never mentioned by participants during post-design discussion. Participants focusing on their phone during anxious situations was a theme in Surveys 1 and 2, as well as this study, but it may be that when given the opportunity the design an object with the express purpose of being pleasant to hold, that form factor was not preferable. It is possible that in real-world use, however, the discretion provided by integrating calming vibrations into a phone would be more valuable than in these participatory prototyping sessions. The majority of stimuli and vibrations were used by different participants when crafting prototypes, further highlighting the benefit of providing a choice of haptic experiences when developing this intervention.

Hypothesis 2 predicted that the most prevalent components used to create prototypes would be soft textures and the phone case. As mentioned, the phone case was unused, but soft textures were the most prominent used, with fur or felt being used on 13 of the 20 prototypes. These were often applied on round objects, or as an optional soft surface on a multi-textured object, and the ability for softness to evoke the comfort of touching pets or plushies was also notable. This motivated making prominent use of soft textures in the higher fidelity prototypes used in the final experiment.

The third hypothesis posited that participants would find their finished comfort objects calming and pleasant to hold. This study provided a key indicator of whether this research direction could produce a haptic intervention would could be calming and thus be beneficially used in social scenarios. The feedback given in the post-session survey supported the potential of these devices as calming interventions, as the majority of participants felt they were pleasant and calming to hold, 85% of participants felt a similar object could be useful in anxious situations and 70% of participants felt that the vibration was an important part of the overall experience.

While feedback from these socially anxious users did indicate that they expected emotionally resonant vibrotactile comfort objects could be beneficial in anxious settings, this experiment did not directly answer Research Question 4, as the prototypes were not formally evaluated during a social exposure event. In the subsequent and final study, Experiment 4, a control and treatment group of socially anxious participants would undergo a social exposure task. Treatment participants would personalise a vibrotactile comfort object beforehand and their social anxiety response would be measured using psychological and physiological measures, to assess if this emotionally resonant haptic intervention had a significant effect.

5.3 Experiment 4: Calming Effects of Emotionally Resonant Vibrotactile Objects in Social Situations

Experiment 4 was used to conduct a formal evaluation of emotionally resonant vibrotactile comfort objects as a calming intervention for socially anxious users during a social exposure event. To accomplish this, participants in a treatment group personalised a haptic comfort object before undertaking a three-minute social exposure task presenting a topic of their choice to a researcher via a video call, while holding their comfort object. State anxiety, the emotional anxiety response happening actively being experienced [57], was measured physiologically and psychologically and compared to a control group which undertook the exposure task with no haptic intervention. The results would answer Research Question 4 - *Can emotionally resonant vibrotactile stimuli be used to calm socially anxious users during social exposure?* - and therefore whether the hypothesised emotionally resonant vibrotactile intervention developed throughout this work had potential to make social exposure more comfortable tolerable and easier to adhere to for socially anxious people.

5.3.1 Methodology

This was a between-subjects experiment designed to observe the state anxiety of two groups of socially anxious users before, during and after a social exposure task using physiological and psychological measures. The first group was a treatment group and participants within it personalised an emotionally resonant vibrotactile comfort object by choosing one of three objects featuring a variety of shapes and textures, then choosing a emotionally resonant vibration from the set used during prototyping, before then holding their object while giving a unprepared three-minute presentation on a topic of their choosing to a researcher via video-call. A control group undertook this task without a haptic intervention and anxiety measures and feedback were compared between both groups. It was expected that, by adopting a personalisation approach, each participant would find at least one emotionally resonant comfort object combination that they preferred, providing a somewhat consistent calming experience between participants despite the lack of consistent responses to each stimulus found in prior experiments.

Three dependant variables were measured to indicate participants state anxiety response: heart-rate, skin conductance and scoring on the State Version of the State Trait Anxiety Inventory (STAI). Section 5.3.2 contains a detailed discussion of how these measures were taken and analysed. The social exposure Behavioural Assessment Task (BAT) used to assess the intervention's impact on social anxiety was a three-minute impromptu presentation on a topic of their choice to another researcher via video call. This BAT has been used several times before to provoke a social anxiety response from participants [26, 90, 113, 114, 180]. Asking participants to choose their own topic, rather than providing one, alleviated the risk of providing topics a participant may not understand or be familiar with, and this approach has been taken in prior work [26, 90, 180]. Initially, this was planned with an in-person audience, as is standard BAT procedure. Due to the restrictions of the COVID-19 pandemic, however, this task was adapted to utilise a video call between each participant and a second researcher. While there is evidence that the face-to-face social exposure of video calls still causes social anxiety [143,165,224], this necessitated approach was somewhat unconventional and so its efficacy was also assessed via observation of anxiety measures in the control group and participant feedback.

This experiment had four hypotheses:

H1: Participants in the control group would experience a significant increase in state anxiety between resting measures and exposure task measures, and would report that the task made them feel socially anxious;

H2: Every comfort object combination option would be utilised by at least one participant;

H3: Participants in the treatment group would exhibit significantly lower state anxiety gain over their resting measures when compared to those in the control group;

H4: Participant feedback would indicate that the emotionally resonant comfort objects were calming to hold, and would be helpful during social exposure.

Hypothesis 1 predicted that the BAT video call would still prompt a significant increase in social anxiety measures. If this did not bear out, then the video call task would not be a suitable method for the study. Hypothesis 2 was founded on the breadth of stimuli and form factor preferences exhibited in prior studies. If H2 bore out and all or the majority of options were utilised, it would support the necessity of providing participants with these customisation options as it would indicate that these allowed them produce a wide variety of comfort objects more finely suited their individual preferences and emotional associations. These stimuli and their delivery inside of a range of comfort objects were informed and developed over the course of four experiments and two surveys to act as a calming intervention for social anxiety during social exposure and Hypothesis 3 formalised the expectation that it would have a significant effect on symptoms, grounded in feedback from participatory prototyping. During prototyping participants rated their impromptu haptic prototypes as pleasant to hold and potentially useful during social exposure and Hypothesis 4 predicted this to repeat for the higher-fidelity comfort object combinations chosen by participants in Experiment 4. The results of the study that confirm or deny Hypotheses 3 and 4 would in turn answer to Research Question 4: *Can emotionally resonant vibrotactile stimuli calm socially anxious users during social exposure?*

5.3.2 Apparatus, Physiological and Psychological Measures

Higher-Fidelity Comfort Object Prototypes

Producing higher-fidelity prototypes allowed each object to be durable for continued use throughout an experiment and built with a solid core and a fitted groove allowing a flush fit of the Haptuator to convey vibration. Three comfort object prototypes were produced based on prominent user preference trends observed in Survey 2 (see Figure 5.6).

(1) The *Haptic Ball* was a stress ball 6.5cm in diameter with a soft furry outer texture. This object served the most prevalent user preferences found during prototyping for texture (*Soft*) and form factor (*Round*) objects. This was the most common single combination of texture and form-factor of the prototypes, appearing in five objects. This object allowed participants to perform squeezing interactions and experience a soft texture filling the hand while experiencing vibrations.

(2) The *Haptic Cube* was a rigid cube with sides 4.3cm in length, five sides with distinct textures for varied haptic experiences, and a slot for the Haptuator on the 6th side. The five textured sides were soft fluffy fur, soft thin felt, smooth thin foam, rough sandpaper and a 6x6 array of Lego studs. This object served the preference for *Multi-textured* comfort objects, while also encompassing preferences found for *Felt*, *Fur*, *Sandpaper*, *Smooth* and *Lego* textures and the *Square* form factor. This object allowed participants to hold the object via the sides they preferred and swap between them for a haptic contrast.

(3) The *Haptic Grip* was a 9cm long Play Dough cylinder built around a rigid cardboard core with clingfilm wrapped around the exterior. It was designed for participants to wrap their fingers around the length and squeeze to form a malleable finger-grip. Five participants built finger-grip comfort objects during prototyping and the *Haptic Grip* embodied both this trend and the prominent preferences for a *Malleable* and *Smooth* object. The cling film wrapped around the Play Dough allowed the object to better retain its shape through repeated exploration.

Physiological Apparatus and Measurement

Heart rate (HR) has been used as an indicator of stress and anxiety in many prior studies [16, 52, 125, 144, 171, 241], and in prior affective HCI research on emotion regulation interventions [11, 38, 62, 87, 169]. A Polar OH1 Optical Heart Rate Sensor[2] was used to record a HR reading every second via Bluetooth. Prior work has also found skin conductance response

[2] Polar OH1. https://www.polar.com/uk-en/products/accessories/oh1-optical-heart-rate-sensor

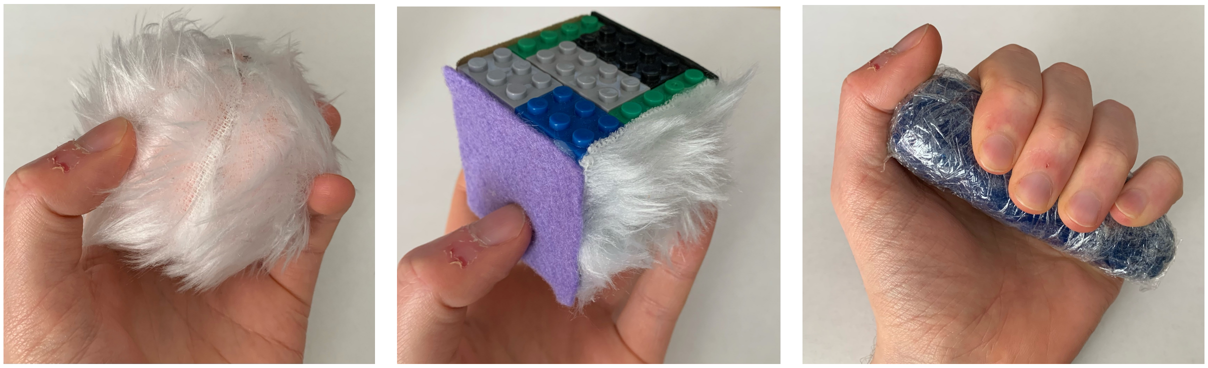


Figure 5.6: The three comfort object form factors: the Haptic Ball, Haptic Cube and Haptic Grip.

(SCR) (also known as electrodermal activity (EDA) or galvanic skin response (GSR)) has a positive correlation with anxiety [125] and it has been used as a physiological measure for anxiety and emotional response in many studies [62, 69, 168, 214]. A BITalino PsychoBIT device[3] and its accompanying OpenSignals (r)evolution software[4] were used to monitor SCR data via two electrodes, with a sample rate of 1000Hz.

Consideration was required when choosing where to place these electrodes. Often electrodes are placed on the hand or the fingers [38, 145, 168] due to their accessibility and sensitivity [219]. In this experiment, however, placement on the hand would interfere with participants using their comfort objects in a natural manner. A study by van Dooren *et al.* [219] measured the most sensitive areas for skin conductance monitoring. Placing them in visible locations, such as the forehead and neck, or in a location which requires partial undress, such as on the foot, abdomen or shoulder, could make users feel more self-conscious during social exposure. The wrist was chosen was the least obtrusive viable location, as it was found to be comparable for measuring the total phasic skin conductance per minute (the SCR measure used in this experiment) to most other sensitive areas.

The SCR signal can be broken into continuous tonic and phasic activities using Continuous Decomposition Analysis [18, 28, 145]. Tonic activity represents long-term baseline SCR per individual, while the phasic component responds in the short term to emotional activity and thus is most important to measure for affective response research [69, 145] This experiment compared the overall level of emotional arousal between a five-minute resting period and the three-minute social exposure task. Continuous Decomposition Analysis was conducted using the MATLAB toolbox Ledalab[5] [18, 19], software used prominently in prior work performing skin conductance analysis [69, 116, 145, 166]. The raw signal data captured by the OpenSignals software was converted into the required microSiemens (μS) electrodermal activity signal for

[3]BITalino PsychoBIT. https://www.pluxbiosignals.com/collections/bitalino/products/psychobit

[4]OpenSignals (r)evolution. https://support.pluxbiosignals.com/knowledge-base/introducing-opensignals-revolution

[5]Ledalab. http://www.ledalab.de

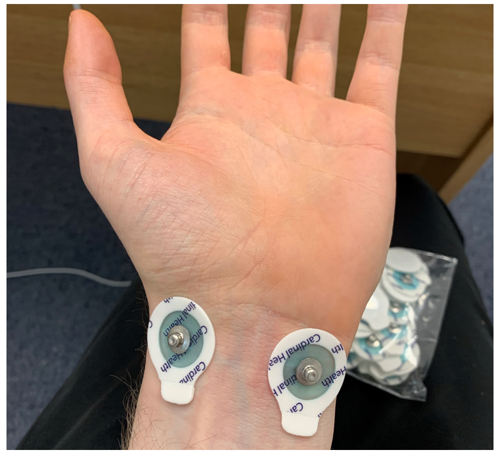


Figure 5.7: Figure showing the placement of PsychoBIT electrodes on a participant's wrist to measure SCR without interrupting comfort object interaction.

Ledalab to analysis using a formula provided in the OpenSignals documentation [6] (See Figure 5.8). Ledalab produced the output measurement 'CDA.AmpSum', the sum of amplitudes of the phasic activity peaks above tonic activity during each measurement period in microSiemens. As the resting measures period and social exposure tasks were different lengths, this was then divided by the number of minutes of observation to produce the skin conductance measure used in this experiment, CDA.AmpSum/Min.

$$EDA(\mu S) = \frac{\frac{ADC}{2^n} \times VCC}{0.12}$$

$$EDA(S) = EDA(\mu S) \times 1 \times 10^{-6}$$

Valid sensor range: $[0\mu S, 25\mu S]$

with:	$EDA(\mu S)$	EDA signal in microsiemens (μS)
	$EDA(S)$	EDA signal in siemens (S)
	ADC	Value samples from the sensor/channel (digital value)
	n	Sampling resolution (default: 10-bit resolution (n=10), although 6-bit may also be found)
	VCC	Operating voltage (3.3V when used with BITalino)

Figure 5.8: Figure showing the formula required to convert the raw SCR sensor signal measured by the OpenSignals software into an electrodermal activity signal which could be analysed by Ledalab. Extracted from the BITalino Electrodermal Activity Sensor User Manual

Psychological State Anxiety Measurement

As in the previous studies, the SIAS was used to screen participants for social anxiety, but this experiment also required the ability to measure short-term state anxiety changes in response to

[6]Bitalino EDA User Manual. https://www.bitalino.com/storage/uploads/media/electrodermal-activity-eda-user-manual.pdf

the social exposure task. This was achieved using Spielberger State Trait Anxiety Inventory - State version (STAI-S) [205] [A.5] which measures a participant's current level of anxiety at the time of undertaking and has been used in many prior works to assess the impact of experimental conditions or treatments [52, 62, 84, 87, 113, 171, 216]. The STAI-S is a twenty-item inventory which asks participants to rate their agreement with statements (e.g. 'I feel at ease') on a four-point scale from 1 (Not At All) to 4 (Very Much So). The resting state anxiety score measured from working adults and college students was between 35.2 and 38.8, as stated by the operating manual (an allowable sample from the manual is provided in the Appendix [A.5] but the full manual cannot be included due to copyright agreement).

5.3.3 Participants

Twenty-nine participants were recruited using university, email and social media channels. Participants were recruited if they were at least eighteen years old and had full haptic perception. One participant was excluded from results due to a low SIAS score indicating they were likely not to be socially anxious, leaving 28 participants (8 male, 17 female, 3 non-binary), 14 randomly assigned to the treatment group and 14 to the control group. Mean participant age was 26.7 (σ = 8.26).

Control														
Participant	P2	P4	P6	P8	P10	P12	P14	P16	P18	P20	P22	P24	P26	P28
Age	32	22	31	27	20	24	21	20	21	21	37	19	27	29
Gender	F	F	F	F	F	M	M	F	F	F	F	NB	M	F
Treatment														
Participant	P1	P5	P7	P9	P11	P13	P15	P17	P19	P21	P23	P25	P27	P29
Age	19	20	20	25	22	33	21	19	32	26	49	51	34	28
Gender	M	F	F	NB	F	M	F	F	M	F	M	F	M	NB

Table 5.4: Ages and genders given by participants who took part in Experiment 4, separated by group. M = male, F = female, NB = non-binary.

5.3.4 Procedure

Participants read an information sheet [B.7.1] before signing a consent form [B.7.2] in order to proceed. Once they had consented to take part, participants were given the SIAS to assess their long-term social anxiety, which could be used to exclude their data from analysis of the results if they were not likely to be socially anxious. Participants were then fitted with the HR monitor and electrodes to monitor SCR. The experiment took place inside a lab room with only the participant and researcher present, both wearing PPE as a COVID-19 precaution. On the table in front of the participant was a computer monitor, a webcam, a button, a pair of headphones and a box containing the components to assemble a haptic comfort object. The experiment took approximately 40 minutes to complete and participants were paid with a £10 Amazon voucher.

Resting Measures

The Polar OH1 which measured HR was placed on the participant's right wrist and the PsychoBIT electrodes which measured SCR on their left wrist (as seen in Figure 5.7). A five minute resting measure was then taken for both HR and SCR, during which participants sat quietly with no external stimuli beyond their immediate surroundings, followed by completion of the STAI. These measures would later be compared to those taken during and after the social exposure task. After this point the procedure varied between participants in the treatment and control groups.

Comfort Object Personalisation

Participants in the treatment group began by customising a comfort object that they would use in the social exposure task. The researcher gave them each of the three form factors, the Haptic Cube, Haptic Ball and Haptic Grip and asked them to explore each one with their hands and choose a favourite. Once they had done so, the researcher fitted the Haptuator inside that object and participants held it while experiencing each of the nine emotionally resonant stimuli utilised in participatory prototyping: *Cat Purr*, *Heartbeat*, *Crashing Waves*, *Rain*, *Small Stream*, *Car Engine*, *Slow Breathing*, *Brushing* and *Underwater Bubbles*, then they were asked to choose a favourite. This resultant combination of preferred form factor and vibration made up each participant's personalised comfort object.

Continuous use of the vibrotactile device during the 3 minute BAT risked haptic adaptation sensation deadening. To avoid this, emotionally resonant vibrations were displayed at normal intensity for ten seconds at a time before their intensity reduced to zero over an interval of one second. After ten seconds without vibration the intensity would return to normal and the vibration would play at normal intensity for ten seconds again. This loop would continue until the researcher stopped the device. Each participant was given a button which allowed them to pause or resume this loop if they wanted during the BAT, in-case the vibration caused distress to a participant during social exposure, but this was never used by any participant.

Social Exposure Task

The researcher then explained the upcoming the social exposure task described in the information sheet to the participant. The researcher readied the video call and audio settings with another researcher, who would act as the audience member, on a laptop facing away from the participant. Once the call was confirmed as functioning correctly, the participant put on the

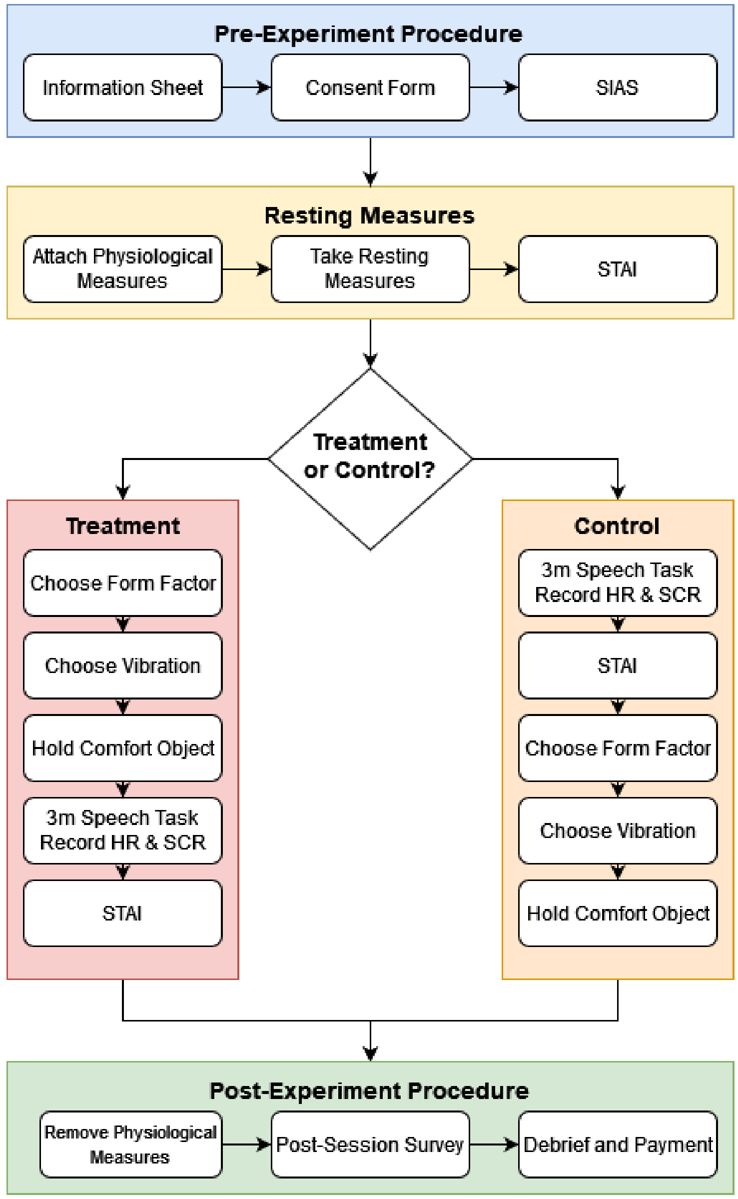


Figure 5.9: Figure showing the procedure for the Experiment. Participants underwent the experimental steps in a different order depending on if they were randomly assigned to the treatment group or control group.

headphones, the vibrations in their comfort object were turned on and they were instructed to hold their comfort object in whatever way they found comfortable throughout the task.

The monitor was then turned on, allowing the participant and audience researcher to see each other and exchange greetings to confirm they could hear each other. Participants were then told that their time to give a three-minute presentation on the topic of their choice was starting and their physiological measurements were initiated. Prior instruction given to the audience member specified that they maintain eye contact with the participant and keep a neutral expression.

Once three-minutes had expired the researcher signalled to the participant that they could stop, physiological measures were stopped and the monitor was turned off and the participant removed the headphones, removing them from the social exposure of the audience member. The participant was asked to immediately complete the STAI once more, then given the opportunity to calm down for a few minutes.

Post-Experiment Procedure

Participants in the control group underwent the same steps as the treatment group, except that the social exposure task was conducted before comfort object customisation and the object was not therefore not held during social exposure. Physiological measures were removed from the participant and a post-session survey was completed [B.7.3] which assessed participant experiences with the social exposure task, their chosen comfort object and their sentiment toward future use of emotionally resonant vibrotactile comfort objects in social settings. Having both groups perform custom object customisation provided more data about form factor and emotionally resonant vibrotactile preferences and allowed them to comment on their comfort object in the post-session survey.

5.3.5 Results

During four of the total 56 SCR measurements the electrodes were dislodged from the participant's wrist, resulting in void data for those measures. Two of these were baseline measurements, while two were task measurements. As a result these datapoints were omitted from the calculation of mean SCR responses and the calculation of proportional SCR gain between baseline and task measurements.

H1 - Control Group State Anxiety Measures

Hypothesis 1 predicted that the exposure task would cause the state anxiety of control group participants to increase, indicating that the BAT adapted to a video-call format was still effective at provoking the expected anxiety response. To investigate if this bore out, three ANOVAs were conducted which searched for significant differences in STAI scores, HR and SCR between resting measurement and exposure task measurement for control group participants. Before these tests were conducted a Shapiro-Wilk Test of Normality was conducted for each measure. Mean heart rate ($p = 0.808$) and STAI scores ($p = 0.533$) were found to be normally distributed. Mean SCR was not ($p < 0.0001$), hence the Aligned Rank Transform was performed before the ANOVA. A significant difference was found for each measure (see Table 5.5).

Control group participants who completed a baseline STAI during resting measures scored a mean of 43.4, while those same participants scored a mean of 52.7 after completing the 3-minute presentation task (see Table 5.6). Mean HR increased from 86.2bpm (beats per minute) at baseline to 93.0bpm during the social exposure task, while mean total phasic skin conductance activity per minute increased from 4.08μS at baseline to 23.2μS during exposure. When asked

Baseline V BAT Measurement - Control	F	Df	P.Value
STAI	15.70	1	**0.0016**
HR	6.766	1	**0.0219**
AmpSum/m	62.24	1	**<0.0001**

Table 5.5: Table showing the outcome of three ANOVAs investigating if there was a significant difference between baseline and BAT measurements for three anxiety measures for control group participants.

in the post-session survey to rate the statement "I found the social task caused me significant social anxiety" on a five-point scale from 1 (Strongly Disagree) to 5 (Strongly Agree), 64% of control group participants agreed or strongly agreed, 21% were neither agreed or disagreed and 15% disagreed or strongly disagreed. These results indicate that the 3-minute speech BAT was successful at prompting an anxiety response from participants, even when conducted via a video-call with a single audience member.

Group	Base STAI	Task STAI	Base HR (bpm)	Task HR (bpm)	Base AmpSum/m (μS)	Task AmpSum/m (μS)
Control	43.43	52.71	86.23	92.98	4.082	23.23
Treatment	44.13	48.67	83.86	86.81	4.521	34.46

Table 5.6: Table showing the mean psychological and physiological anxiety measures for participants in the control and treatment groups at both during a baseline resting measurement and social exposure task measurement.

H2 - Comfort Object Personalisation Preferences

Hypothesis 2 predicted every comfort object and emotionally resonant vibration option to be used by at least one participant. This bore out, as every option was utilised at least once (see Table 5.7). There was spread in stimulus preference as half the participants chose the two most popular stimuli (*Car Engine*: 8, *Cat Purring*: 6), while five of the nine stimulus options were chosen by only one or two participant(s). Participant feedback indicated that providing this set of nine stimuli to choose from was an effective strategy, as when asked to rate the statement "I was able to choose a vibration which I connected with and found pleasant" on a five-point scale from 1 (Strongly Disagree) to 5 (Strongly Agree), 57% of people strongly agreed, 39% agreed, while only one person strongly disagreed. When choosing which of the three comfort object form factors to use, the *Haptic Cube* was the least popular, chosen by five participants, while the *Haptic Grip* was chosen 13 times and the *Haptic Ball* 10 times. When asked to rate the statement "*The comfort object I chose was suited to my preferences*", 28% of people strongly agreed, 57% agreed and 14% neither agreed or disagreed.

Object	n			Stimulus	n		
Grip	13	Car Engine	8	Slow Breathing	3	Raindrops	1
Ball	10	Cat Purring	6	Brushing	2	Heartbeat	1
Cube	5	Small Stream	4	Crashing Waves	2	Underwater Bubbles	1

Table 5.7: Table showing how often each object form factor and each emotionally resonant vibrotactile stimulus were chosen in total by participants in Experiment 4 when customising their preferred comfort object.

H3 - Treatment Group Versus Control Group State Anxiety

Hypothesis 3 predicted that treatment group participants would experience a significantly smaller increase in anxiety measures between the social exposure speech task and resting measurement compared to participants in the treatment group, which would indicate that the personalised comfort objects had a calming effect. To investigate this, three two-way ANOVAs were conducted to investigate whether there was a significant difference in the three anxiety measures, STAI, HR and SCR, between both resting and speech task measurements and between control and treatment groups, blocked by participant [11]. Again, Shapiro-Wilk tests revealed a normal distribution for mean HR ($p = 0.567$) and STAI scores ($p = 0.307$) and not for SCR ($p < 0.0001$). A significant was found for all three anxiety measures between baseline and BAT measurement, but no significant different was found between control and treatment groups, and there were no interaction effects (see Table 5.8 and Figure 5.10).

ANOVA - Effects on Mean Heart Rate (bpm)	F	Df	P.Value
Measurement Time: Baseline or Task	8.541	1	**<0.05**
Condition: Control or Treat	0.517	1	0.478
Interaction between Measurement Time and Condition	1.830	1	0.188
ANOVA - Effects on SCR (AmpSum/m)	**F**	**Df**	**P.Value**
Measurement Time: Baseline or Task	42.59	1	**<0.001**
Condition: Control or Treat	0.498	1	0.487
Interaction between Measurement Time and Condition	0.940	1	0.342
ANOVA - Effects on State Anxiety Score (STAI)	**F**	**Df**	**P.Value**
Measurement Time: Baseline or Task	8.586	1	**<0.05**
Condition: Control or Treat	0.058	1	0.811
Interaction between Measurement Time and Condition	1.888	1	0.181

Table 5.8: Table showing the outcome of three ANOVAs investigating whether there was a significant difference between baseline and task measurement and the control group and treatment group for each anxiety measure, blocked by participant.

Having previously observed a significant difference within the control group between baseline and task anxiety measurement for all three anxiety measures, three further ANOVAs were

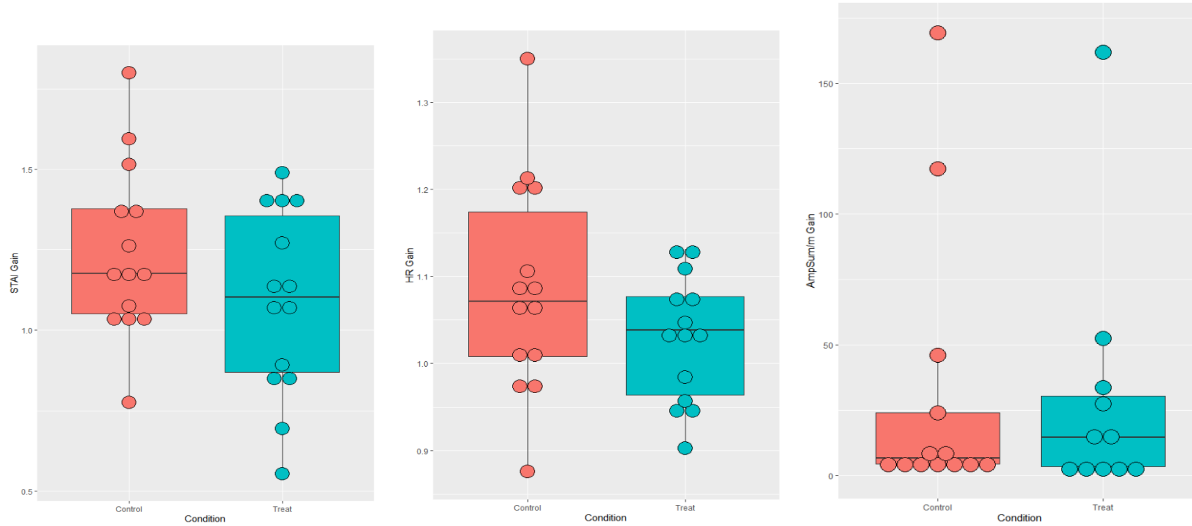


Figure 5.10: Three graphs showing the box-plots comparing the distribution of the proportional increases in STAI, HR and SCR anxiety measures for participants in control and treatment groups.

used to establish if this held true within just the treatment group. There was still a significant difference between baseline and task SCR measurement ($F = 62.24, Df = 1, p = 0.0007$), but unlike the control group, there was no significant difference between baseline and task measurements of STAI and HR (see Table 5.9). A side-by-side comparison of speech task STAI scores between the control and treatment group shows a difference in distribution (see Figure 5.11). The Standard Deviation of STAI scores was 10.4 for the control group and 15.58 for the treatment group and the control group interquartile range of speech task STAI scores was 8.25, compared to the treatment group interquartile range was 28.0. A chi-squared test was conducted and found a significant difference in the interquartile distribution of treatment participants' STAI scores across the full range of responses, when compared to the distribution of control group participants' scores ($\chi^2 = 18.63,\ df = 3,\ p < 0.05$). This may suggest that, while Hypothesis 3 cannot be accepted due to finding no impact significant difference in anxiety measures between groups, haptic comfort objects can impact participants perceptions of their own anxiety, as self-reported in the STAI, but this effect was inconsistent across individuals.

Baseline V Speech Task Measurement - Treatment	F	Df	P.Value
STAI	1.146	1	0.3024
HR	3.536	1	0.0810
AmpSum/m	62.24	1	**0.0007**

Table 5.9: Table showing the outcome of three ANOVAs investigating if there was a significant difference between baseline and speech task measurements for three anxiety measures for treatment group participants. P values which indicated significant main effects are marked in bold.

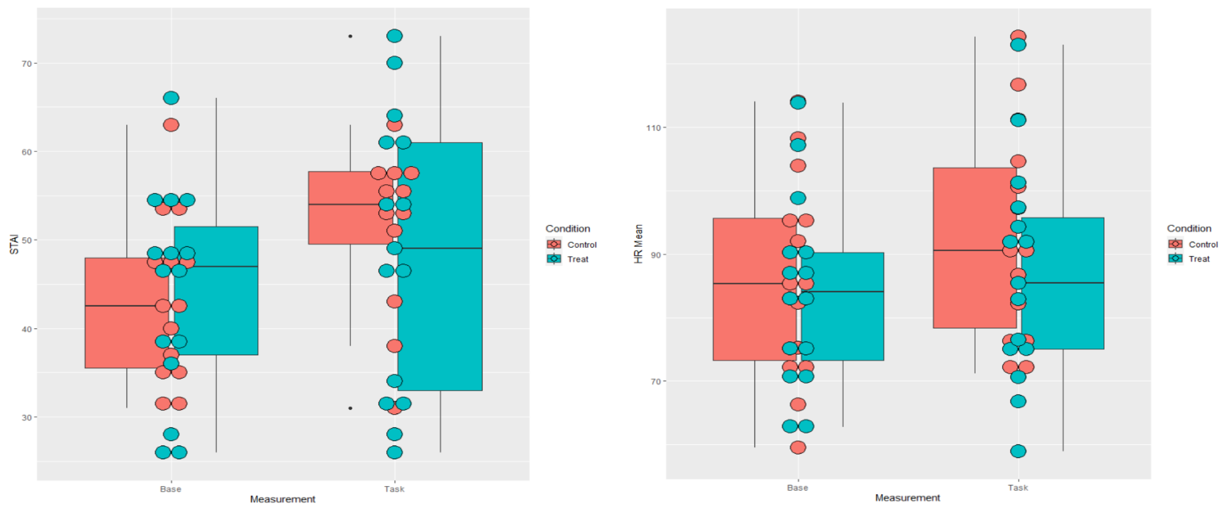


Figure 5.11: Two graphs which compares the control group and treatment group distribution of average STAI and HR at both base and speech task measurements.

H4 - Participant Comfort Object Sentiment

The final hypothesis stated that participants would consider the haptic comfort objects as calming to hold and useful during social exposure, an expectation grounded in similar feedback garnered during participatory prototyping. This expectation was investigated with the post-session survey which contained three relevant Likert-scale questions and two open-ended questions where participants could provide reasoning for their responses (see Figure 5.12). Feedback indicated that the majority of participants viewed their comfort objects and the emotionally resonant vibrations as calming and effective, as well as potentially helpful in anxious situations. When asked to rate the statement “The comfort object I chose made me feel comforted or calm when held” on a scale of 1 to 5, where 1 meant Strongly Disagree and 5 meant Strongly Agree, 78% agreed or strongly agreed and 14% were neutral. When asked if the “vibrations made the comfort object more effective” 68% agreed or strongly agreed and 21% were neutral. Finally, when asked to rate the statement “I could see objects like my chosen comfort object being helpful when I am in an anxious situation” 43% strongly agreed, 36% agreed and 18% were neutral. As only half the participants who gave feedback (those from the treatment group) had experience using their comfort object during the social exposure task it, a pair of ANOVAs (following ARTs) were used to investigate if the group a participant was assigned to impacted how anxious they reported feeling in the post-session survey or how useful they thought their comfort object was. The ANOVAs searching for a main effect of participant group on to two statements: (1)“I found the social task caused me significant social anxiety” and (2) “I could see objects like my chosen comfort object being helpful when I am in an anxious situation”. No significant difference was found between the responses of control group and treatment group participants ((1) F=0.1814, Df=1, p=0.0674; (2) F=0.1904, Df=1, p=0.6617).

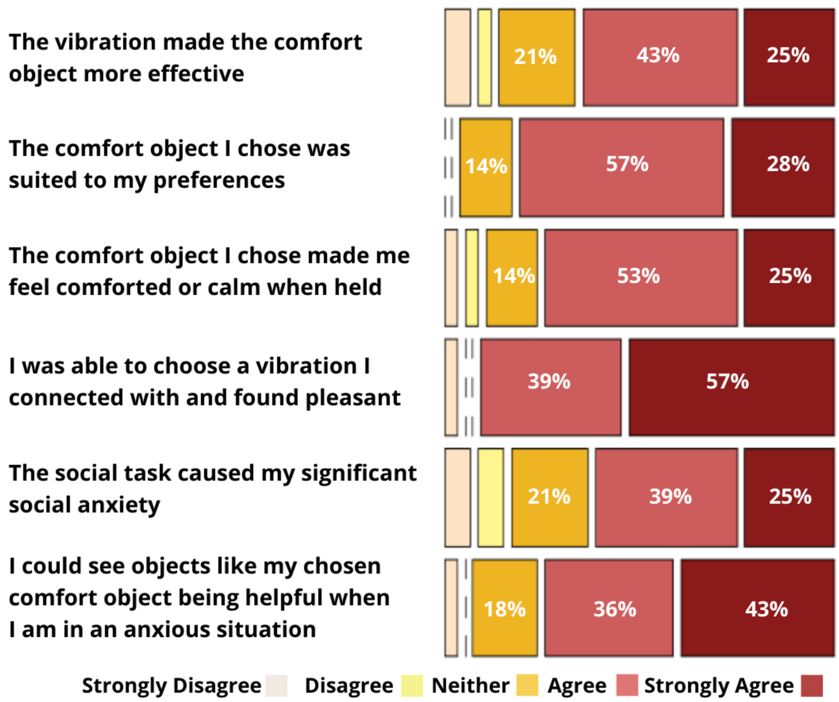


Figure 5.12: Experiment 4 post-session survey results indicating participant sentiment how calming and helpful they felt their comfort object was.

Participants were asked to explain whether or not they felt their comfort object would be useful in future social exposure in an open-ended qualitative survey question. The responses to these questions were assigned themes to identify pertinent trends. Fifteen participant responses noted that the haptic comfort objects could enable *Attentional Redeployment*, distracting them from their physiological or psychological anxiety symptoms.

> P13: "The object was a good distraction, in the sense that my senses were distracted, which is typically helpful for anxiety."

> P21: "It's helpful to have something to hold and distract you from just the anxiety right in front of you. Especially when it is something so mindless, like squeezing the dough, yet it helps ground you and bring you away from the anxiety. The vibrations were a nice gentle reminder to relax, breathe and present."

Eighteen participants specifically mentioned the emotionally resonant vibrations, with 11 people noted they were *pleasant* or *calming*. Five of them specifically noted that their emotional response was tied to emotional resonance and six wrote that the vibrations allowed them to feel more grounded or focused, signalling a potential for in-the-moment *Cognitive Change*.

> P9: "It reminded me of holding a small animal (fluffy ball with cat purring), which has always helped me reduce anxiety."

> P8: "I chose the stress ball with the fur. It would have been helpful in a stressful situation as I can squeeze it, 'pet' it and pass it from one hand to another. The vibrations were also helpful - especially the slow heartbeat - because it could make me concentrate and focus, also remind me how to breathe."

Three participants noted they during the speech task they did not notice the vibrations as they were "too nervous" or "couldn't pay attention", highlighting that some users will not have the capacity to effectively split attention between social interaction and an external haptic stimulus or any calming effects.

Eleven comments were about comfort object *form factor*, i.e. shape and texture, highlighting how the specific touch interactions afforded by different objects could be important. Nine participants mentioned squeezing or kneading interactions; for example:

> P1: "I was able to focus on kneading the play-dough if I was feeling overwhelmed"

> P18: "Sometimes when I am anxious, I just want to squeeze something tightly or break something to release tension. The gripping object is something that can be grabbed/squeezed without consequences (I often don't have an object to squeeze and end up squeezing myself which sometimes makes my anxiety worse)."

The prevalence of these interactions may explain why the Haptic Cube was the least popular form factor, as it was the only fully rigid object. The practicality of the objects in real conversations was of concern to three participants who were worried about drawing attention to themselves or that they obstructed their normal behaviour.

> P4: "[I would be] worried now others would perceive me using it in social situations"

> P5: "I use my hands when I talk so, while comfortable, it would hinder how I express myself."

Comfort objects which are smaller or wearable (for those who do not desire to directly interact with the object) could be more discrete and less obstructive, addressing these issues in real-world use cases.

5.3.6 Discussion

Experiment 4 was a between-groups evaluation of personalisable emotionally resonant vibrotactile comfort objects as a calming intervention for socially anxious participants during social exposure. Anxiety was measured using one psychological measure, the STAI, and two physiological measures, heart rate and skin conductance, and these were observed first during a baseline resting measurement and then again during and after a three minute social exposure speech task. Participants in the treatment group chose their preferred combination of form factor and vibration, then held the resulting comfort object throughout the speech task, while control group participants chose their preferred object after completing the task without it.

As this experiment used an established 3 minute presentation task adapted to an online video-call format due to COVID-19 restrictions, it was important to establish that this task still produced an anxiety response in socially anxious participants. This was confirmed when control group participants exhibited a significant increase in all three anxiety measures, mean STAI score, HR and SCR, between baseline and speech task measurements. This allowed this experiment to function under COVID-19 conditions and could allow for future researchers to utilise BATs under limiting circumstances in future. A comparison study between in-person and online BAT speech tasks would better inform their relative efficacy.

Having established that the online BAT successfully induced social anxiety, the primary aim of this experiment was to observe if holding a personalised emotionally resonant vibrotactile comfort object had an impact on a participant's anxiety response. Despite the fact that the majority of participants rated their comfort objects as calming and pleasant to hold, and felt they would be useful in future social scenarios, participants in the treatment group who used the intervention did not exhibit a significant difference in anxiety measures when compared to control group participants. Given the breadth of haptic preferences found in Chapter 3, Chapter 4, and in prototyping, participants were provided with a selection of comfort objects and emotionally resonant vibrations to choose from, in an effort to provide each participant with an experience suited to their own preferences and therefore normalise efficacy of the intervention between participants. This did not, however, result in a consistent effect across users and this evaluation found no evidence that emotionally resonant vibrotactile comfort objects have any significant impact on the physiological symptoms of anxiety.

The only notable difference between groups was a wider STAI score distribution for treatment group participants, which led to there being no significant difference between STAI scores measured at baseline and after the BAT for treatment participants. Considering this alongside positive participant feedback indicates that the vibrotactile comfort objects caused only some participants to exhibit less psychological anxiety symptoms and view themselves as less anxious, an effect which may have contributed to participant sentiment that the objects would be useful in future social interactions. Participant qualitative comments which describe feeling more "focused", "calm" or "grounded" while holding their object or experiencing the emotionally resonant vibrations further supports this.

The results of Experiment 4 indicate that some users may find that interacting with an emotionally resonant vibrotacile comfort object reduces their psychological anxiety symptoms. The majority of participants were also successful in personalising a vibrotactile comfort object that they felt was calming and would be useful in future social scenarios. There was, however, no evidence of any reduction in physiological symptoms or a consistent *reduction* in psychological anxiety symptoms for those who used the object during face-to-face social exposure. The following sections will discuss the final evaluation result in wider context of the thesis and in relation to Research Question 4.

5.4 Chapter 5 Discussion

The work in Chapter 5 used a personalisation approach alongside socially anxious participants to first prototype the design of comfort objects to house emotionally resonant vibrotactile stimuli, then evaluate whether participants holding these objects with their preferred combination of form factor and vibration experienced a significant calming effect on anxiety response during face-to-face social exposure.

5.4.1 Participatory Prototyping

The participatory prototyping sessions defined how the emotionally resonant stimuli should be housed and presented by allowing socially anxious users to build comfort objects they found pleasant and calming to hold. These stimuli were augmented with a Haptuator to produce impromptu vibrotactile comfort object prototypes. Participants chose their preferred emotionally resonant stimulus and gave preliminary feedback on their experience using their object and its usefulness in future social scenarios.

Every vibration was preferred by at least two participants. This supported the specific stimuli included in the set following their development in the first three experiments. It also supported the approach of providing users with a selection of emotionally resonant stimuli to choose from, which allowed each individual to find multiple pleasant cues within that set. Prominent shape, texture and exploratory procedure trends were identified in the selection of the comfort objects prototyped by participants. These trends were used to create three higher-fidelity comfort object prototypes used in Experiment 4, but also more generally inform the development of holdable affective objects designed for socially anxious users or other Attentional Redeployment applications. It also lent support to providing users with options for comfort object form factor, rather than forcing all users to one object that the majority would have have designed or chosen if given the choice.

Participants reported that the objects were suited to their preferences, pleasant to hold and felt they could be useful in social scenarios. This was a promising indication of an answer to Research Question 4, that with all the affordance of customisation these emotionally resonant haptic objects could be a calming intervention. This could not be confirmed, however, until this was formally evaluated during a social exposure task in the final study Experiment 4.

5.4.2 Experiment 4

In Experiment 4, the set of three higher fidelity comfort object prototypes and nine emotionally resonant stimuli were used in a final evaluation study. Treatment group participants chose a comfort object with their preferred form factor and vibration, then held their comfort object during a 3 minute social exposure speech task, while control group participants performed the task with no comfort object. There was no significant difference in anxiety measures between groups across all three measures, indicating that emotionally resonant vibrotactile comfort objects had no consistent impact on social anxiety or calming effect. Given this, emotionally resonant vibrotactile comfort objects cannot be considered as a generally effective calming intervention for social exposure.

There were indications that these comfort objects can impact subjective anxiety measures. Treatment group participants did exhibit a significantly wider interquartile distribution of STAI scores than control participants, to the extent that there was no significant difference between baseline and speech task STAI scores for treatment group participants. In addition, most participant feedback stated they felt their comfort object was calming to hold and could be useful in future social scenarios. This could mean that emotionally resonant vibrotactile stimuli are a useful intervention for some individuals to provide subjective psychological comfort, but they would first need to be customise the intervention to their preferences and then assess if they are useful for that individual.

Positive participant feedback regarding their vibrotactile comfort objects also reinforces the potential for these cues and objects to evoke pleasant and positive emotional responses that was indicated throughout the thesis. While their ability to impact social anxiety symptoms is limited, future work investigating the use emotionally resonant vibration in other applications would be valuable to understand how they are best to be utilised.

5.5 Conclusions and Research Question 4

Chapter 5 presented two experiments designed to answer Research Question 4:

Research Question 4: Can emotionally resonant vibrotactile stimuli calm socially anxious users during social exposure?

Despite choosing their preferred stimulus and comfort object, emotionally resonant vibrotactile comfort objects did not affect a consistent reduction in anxiety measures when compared to a control group, indicating that this is not an effective calming intervention for social anxiety. The wide distribution of treatment group participant STAI scores does, however, provide evidence that some participants were calmed by interacting with their vibrotactile comfort objects during social exposure. In addition, the majority of participants in both Experiments 4 and 5 agreed or strongly agreed that their vibrotactile comfort objects were pleasant or calming to hold and could be helpful in future social scenarios. Finding the object calming or pleasant to hold was also a prominent theme in Experiment 4 qualitative analysis, although more participants cited the main benefit of their comfort object as a tool which allowed them to redeploy attention away from their anxiety symptoms and focus better on the exposure task. The vibrotactile stimuli were not solely responsible for any participant responses, as their experiences were also impacted by the ability to personalise the object which delivered emotionally resonant vibrations, and participants were able to fully customise the comfort object during participatory prototyping and choose from a varied set of objects in Experiment 4. Prototyping participants strongly agreed that the shape and texture of their comfort object was important to their experience than the vibration. Future work which directly compared the emotional responses and participant feedback between experiencing emotionally resonant vibrations via (1) personalised comfort objects or (2) generic devices, like a phone or smartwatch, would be valuable in identifying how strong a role using comfort objects had on user experience.

Addressing Research Question 4 with the findings of Experiments 4 and 5 in mind, it is clear that emotionally resonant haptics *can* reduce one's perception of ones' own anxiety during social exposure for specific socially anxious individuals during social exposure, and most participants felt their haptic comfort objects were calming. There is, however, no evidence that this effect will occur across a majority of individuals within the population and no evidence that emotionally resonant haptics can reduce physiological anxiety symptoms during social exposure. Notably the majority of participants in both groups believed that a comfort object like the one they customised could be useful in future stressful situations. If people perceive that a vibrotactile comfort object will be useful in these settings, it could make them feel more confident in attending them, potentially still addressing the adherence challenge of exposure therapy. While investigating this point fell out of the scope of this thesis, this is a valuable question for future work.

Throughout the thesis, these stimuli were successful in eliciting varied emotional responses and evoking meaningful emotional experiences not observed by prior affective vibrotactile research. This does widen the applicability of simple vibrotactile actuators in affective computing interfaces, with results dependent on a users preferences and their ability to personalise their experience. The next chapter will summarise the findings of the entire thesis in relation to all four research questions, discuss limitations and make recommendations for future work and applications.

Chapter 6

Conclusions

This thesis investigated using emotionally resonant vibrotactile stimuli as a calming intervention for socially anxious users during social exposure. The thesis statement was as follows:

> This thesis investigates using affective haptics as a calming intervention for socially anxious users to reduce the difficulty and discomfort of social exposure. This research developed a novel category of vibrotactile stimuli which evoke real-world sensations to elicit calming emotional responses, termed emotionally resonant vibrations, and used them to augment comfort objects informed by participatory prototyping alongside socially anxious users. Although no consistent significant effect on physiological anxiety symptoms was found, results showed that interacting with personalised emotionally resonant vibrotactile comfort objects can reduce the subjective anxiety of some socially anxious people, and that these users viewed these haptic objects as both calming and helpful in managing their anxiety symptoms.

This thesis statement is based on the research discussed in the prior three chapters. Motivated to provide calming feedback to socially anxious users discreetly during social exposure, Chapter 3 presented the development of a novel category of affective vibrotactile stimuli, emotionally resonant vibrations, which leveraged participant associations with calming real-world phenomena to elicit more varied and meaningful emotional responses than stimuli used in prior work. Chapter 4 described two surveys which drove the development and use of these stimuli as a calming intervention, observing how socially anxious users currently perform emotion regulation during social exposure and providing an empirical foundation for the design of emotionally resonant haptic comfort objects by categorising haptic preferences for texture, form factor and which calming real-world phenomena people could wish to be evoked by emotionally resonant vibrations. Chapter 5 utilised participatory prototyping with socially anxious participants to develop calming vibrotactile comfort object prototypes, informing the design of a personalisable emotionally resonant vibrotactile intervention which was then evaluated in a between-groups study to assess its impact on social anxiety measures and participant sentiment. The findings of these studies were used to answer four Research Questions. These findings will be summarised in this chapter and subsequent contributions and limitations of the thesis will be discussed, followed by suggestions for future work.

6.1 Research Question 1

Can single-actuator vibrotactile stimuli be emotionally resonant of real-world sensations?

Three experiments, discussed in Chapter 3, were conducted to answer this question. Experiment 1 was used to inform using a duration of 10 seconds for single-actuator stimuli used in all the following research, in order to avoid adaptation and sensation deadening. Experiment 2 presented an initial observation of participant's affective ratings and qualitative feedback regarding a set of eight single-actuator vibrotactile stimuli generated from sound recordings of real-world phenomena. It was clear that vibrotactile stimuli conveyed from a single actuator could be emotionally resonant, as every participant was able to find at least one stimulus emotionally resonant, and two stimuli on average. Participants predominantly experienced a pleasant emotional response to stimuli which evoked past positive experiences, but some participants did also have negative associations with certain stimuli. Generally, it was observed that preferences for specific stimuli varied greatly between people.

Experiment 3 followed up on Experiment 2 by observing affective responses to (1) a wider set of 15 emotionally resonant stimuli and (2) existing stimuli used in prior work, allowing for a direct comparison of affective range between the two. Participant ratings for emotional resonance were also measured after each stimulus was presented, along with affective responses. The set of emotionally resonant stimuli exhibited a wider affective response range than existing abstract cues when plotted on Russell's Circumplex Model of Emotion, notably with a comparatively higher valence range and lower arousal range, desirable for eliciting pleasant or calming emotional responses. Five stimuli had positive average emotional resonance across all participants, but qualitative feedback continued to reinforce that participant preference was still very individual, as a vibration which is meaningful and affective for one person may be meaningless and abstract for another. Thus, while average emotional resonance indicated which stimuli had wider average applicability between users, stimuli with lower average resonance may still be highly resonant and effective for specific individuals.

Addressing Research Question 1 with the findings of Experiments 1, 2 and 3: vibrotactile stimuli generated from a single actuator can be emotionally resonant, resulting in more meaningful and varied emotional responses than existing abstract cues. The ability to find a specific stimulus emotionally resonant varied from person to person, however, so providing a set of emotionally resonant vibrations will increase the likelihood of providing each user with a stimulus that works for them.

6.2 Research Question 2

Can thermal cues be used to enhance the emotional resonance and affective range of vibrotactile stimuli?

Experiment 3 addressed this question by presenting the set of 15 emotionally resonant vibrotactile stimuli at a cool, neutral and warm temperature to observe if there was any impact of temperature level on participant's affective response and emotional resonance ratings. Temperature had several effects. Presenting a stimulus at a warm temperature level had a small but significant positive effect on the valence and arousal of the resultant sensation, making them more pleasant and alerting. One stimulus, *Heartbeat*, was found to be less emotionally resonant when presented at a cool temperature level than a neutral or warm level, while the *Small Stream* stimulus was significantly more emotionally resonant when presented cool, rather than warm. While only these two stimuli exhibited a statistically significant effect across the participant set, qualitative data once again revealed, as found throughout the thesis, a plethora of experiences too inconsistent between participants to amount to a wider statistical trend. Stimuli like *Cat Purring*, *Heartbeat* or *Car Engine* were highlighted as more resonant when warm and less so when cold, and water stimuli like *Small Stream* or *Underwater Bubbles* could change their meaning based on temperature, from cool and relaxing to boiling. A consistent theme was that participants only discussed the impact that temperature had on stimuli with an 'expected' temperature (e.g. *Cat Purring* and warmth or water stimuli and cold). To answer Research Question 2: thermal cues have a small but consistent effect on the valence and arousal of emotionally resonant vibrations and can have a significant effect on how resonant participants perceive specific stimuli to be. The emotional resonance of stimuli which befit the presented temperature level could be enhanced and the resonance of stimuli presented at the 'wrong' temperature was reduced, although effects on certain stimuli varied between individuals and were only consistent across participants in three instances.

6.3 Research Question 3

Which calming real-world experiences would users prefer emotionally resonant vibrotactile stimuli to evoke and what factors impact their use in social settings?

Two surveys presented in Chapter 4 were used to address Research Question 3. The first of these surveyed socially anxious users on two topics: (1) how they currently attempted to regulate their emotion and how effective they felt those techniques were, and (2) how they currently perceive different kinds of affective touch as a calming intervention for social anxiety. Socially anxious respondents mostly used safety behaviours that utilised avoidance strategies to manage their anxiety symptoms, motivating the need for an intervention which could help them manage these symptoms through discrete use during social exposure. When asked how they currently perceived affective touch as a calming intervention, three factors were found: participants overwhelmingly indicated that they preferred private touch to indiscreet and public touch and preferred touch with a pet or romantic partner rather than touch with friends, family or objects. The design space of real-world experiences that emotionally resonant stimuli should aim to evoke when attempting to elicit calming emotional responses was still unclear. This point was tackled by the second survey.

Survey 2 asked respondents to imagine themselves in four different social settings, suggest a haptic or auditory sensation they would find calming in that scenario, then select any sensations they felt they would find calming from a list of eighteen possible emotionally resonant stimuli. The four social scenarios were varied by whether they were public or private spaces as well as whether the social exposure described was intimate or not. Participants suggested a wide array of sensations which were then assigned qualitative codes to identify prominent trends. These codes were grouped into four categories of experience: Human, Social, Artificial and Natural. More prominent codes within these categories included touch from a *Hand*, *Animal Touch*, *Music* and *Warm Mug* and the most common shared attributes between codes included *Warm*, *Background Sound*, and *Soft*. The imagined social scenario influenced participant responses by biasing suggestions toward sensations which could naturally occur in that scenario (e.g. holding a warm mug in a café setting), but this effect was less pronounced when participants instead picked from a list a pre-selected stimuli. The *Job Interview* scenario was an exception, participants were significantly more likely to suggest calming natural sensations (e.g. the sound of rain), perhaps because participants could not bring to mind any diagetic calming sensations for a job interview and so defaulted to more generically calming experiences.

To address Research Question 3: there is a broad range of real-world phenomena users may find calming to experience, but there are prominent trends within the categories of social, human, natural and artificial experiences. Each persons' unique lived experiences impact the real-world phenomena they find resonant and their associated emotional responses, but using a set of emotionally resonant stimuli which evoke examples of these prominent trends gives a better chance of providing each user with at least one cue they would find calming and emotionally resonant, without crafting a specific stimulus for each individual. There are also factors which could impact user preference for an affective touch intervention: whether the touch can be directly observed by others and whether the sensation feels diagetic or appropriate to the specific social scenario.

6.4 Research Question 4

Can emotionally resonant vibrotactile stimuli calm socially anxious users during social exposure?

This question was addressed by two experiments in Chapter 5 which put personalised emotionally resonant vibrotactile comfort objects into the hands of socially anxious people. Participatory prototyping with socially anxious users was then conducted to inform the design of comfort objects which would house the emotionally resonant vibrations. It also provided an initial opportunity to acquire feedback from socially anxious users about their experiences interacting with their emotionally resonant vibrotactile comfort object, and whether they felt they could be calming or useful in social scenarios. Feedback was positive, as most participants agreed or strongly agreed that their object was pleasant to hold and felt that similar devices could be helpful in anxious situations. While the shape and texture of the prototype comfort objects was most important to participants, 70% felt that the emotionally resonant vibrations were an also important part of the overall experience. Although these results were promising, an empirical evaluation of this intervention was required to draw more concrete conclusions, Experiment 4, which formally assessed its efficacy at reducing anxiety symptoms during social exposure.

Experiment 4 evaluated whether socially anxious participants in a treatment group, who personalised and interacted with an emotionally resonant vibrotactile comfort object, exhibited significantly lower anxiety symptoms during a three-minute social exposure task, when compared to a control group. Anxiety was assessed with both physiological measures (heart rate and skin conductance) and with a psychological measure (the State Trait Anxiety Inventory - State Version [A.5]) and participant feedback was again elicited at the end of the session. No significant difference was found in the increased anxious responses caused by the social exposure task between the control and treatment groups. There was, however, a notable statistical result: the distribution of Psychological anxiety scores (via the STAI) was significantly wider for treatment group participants when compared to the control group. Due to this breadth of this distribution, there was no significant difference between STAI scores taken at rest and taken immediately following the social exposure task for participants who held their comfort object throughout the task. This indicates that interacting with the emotionally resonant vibrotactile comfort objects caused a portion of treatment group participants to experience a reduction in their psychological anxiety symptoms, while others were not affected. This was further supported by positive participant feedback. As in prototyping sessions, a large majority of participants agreed or strongly agreed that they found interacting with their comfort object to be calming and that they could see it be being useful in future anxious scenarios. To answer Research Question 4: there is some evidence that emotionally resonant haptics can reduce the psychological anxiety symptoms of a subset of socially anxious users, allowing them to feel calmer during social exposure, but this is not a consistent effect across users and there is no evidence to suggest that such an intervention will result in reduced physiological anxiety symptoms.

6.5 Contributions and Recommendations

This thesis makes four main contributions to the fields of affective haptics and HCI interventions for social anxiety. These are:

1. developed a novel category of vibrotactile stimuli, emotionally resonant stimuli, and observed their ability to elicit more varied and meaningful emotional responses than existing stimuli;

2. demonstrated that presenting emotionally resonant cues alongside different temperature levels can widen their affective range, and can increase or decrease their emotional resonance depending on the expected temperature of the real-world phenomena being evoked;

3. surveyed and categorised the varied haptic preferences of socially anxious users, as well as their use of affective touch and emotional regulation techniques, informing the future design of haptic interventions for use in socially anxious settings;

4. first evaluation of the efficacy of emotionally resonant vibrotactile comfort objects as a calming intervention for socially anxious users during social exposure.

6.5.1 Design Recommendations

These contributions have been used to make a set of design recommendations for future work in related fields.

Utilising Emotionally Resonant Vibrotactile Stimuli

1. Stimuli with a duration of 10s allow enough time for the complete presentation of the acoustic waveforms of natural phenomena, like crashing waves, without suffering from haptic adaptation.

2. Single actuator vibrotactile stimuli can be emotionally resonant of real world phenomena and can elicit associated emotional responses. This opens up new opportunities for interface designers to evoke meaningful sensations with the addition of simple haptic cues.

3. Both the ability to find each specific stimuli emotionally resonant, and the resultant emotional response, varies between individuals. While the best performing stimuli, like *Cat Purring*, can be resonant across a large portion of users, it is most appropriate to provide a varied set of emotionally resonant cues to accommodate the varied preferences of a population.

4. Several emotionally resonant cues trialled by this thesis did not garner either promising average emotional ratings or evoke strong reactions from any individuals: *Vacuum Cleaner*, *Dog Growling*, *Muffled Conversation*, *Wind*, *Scratching* and *Train Tracks*. This supported their exclusion from the emotionally resonant stimuli set.

5. Warm temperature levels have a small, but significant, positive effect on the valence and arousal of emotionally resonant cues. Thermotactile cues can be used to make these stimuli more prominent and pleasant, providing the interface can accommodate their practical limitations.

6. Thermotactile cues can enhance or reduce the emotional resonance of vibrotactile which evoke natural phenomena with an associated temperature.

7. Emotionally resonant vibrations can be effectively conveyed through of both rigid and non-rigid materials, showing the potential for these stimuli to augment a variety of objects and devices.

Designing Affective Haptics Comfort Objects for Socially Anxious Users

1. Qualitative participant feedback from throughout the thesis highlighted that the fear of being judged or observed made calming affective touch a less viable intervention for socially anxious users. Haptic comfort objects intended for public use should offset this by prioritising form-factors that allow for discrete use.

2. Most participants agreed that the form-factor and texture of personalised vibrotactile comfort objects was more important to the overall experience than the vibrotactile stimulus, highlighting the value of these elements to a haptic intervention.

3. Haptic comfort objects should allow personalisation or choice of form-factor and texture as varied preferences were observed between participants.

4. No difference in physiological anxiety symptoms was found between participants using the intervention and the control group. Emotionally resonant vibrotactile objects should not aim to manage these symptoms, but rather facilitate emotion regulation and the reduction of psychological anxiety symptoms.

5. Treatment group participants exhibited a wide distribution of subjective psychological anxiety measures. The majority felt that the object was calming to hold and could be helpful in social settings. Given this, emotionally resonant vibrotactile comfort objects have the potential to aid in the management of psychological anxiety symptoms, but variably between users.

6.6 Limitations and Future Work

This section outlines the limitations of the research discussed in this thesis and proposes future work which could address these limitations.

6.6.1 Emotionally Resonant Stimuli Selection

Via a pair of experiments and one survey, a total of 16 different acoustic waveforms of real-world phenomena were trialled as emotionally resonant vibrotactile stimuli and a set of effective cues were identified and used to augment personalised comfort objects. It is likely, however, that there are other effective emotionally resonant stimuli which can be presented from a single vibrotactile actuator which were not trialled and some emotionally resonant stimuli that were trialled may be as or more effective when utilising multiple actuators. Further exploration of this design space would prove valuable. One approach could be to work alongside specific users over a longer to iteratively craft stimuli suited to their specific experiences.

6.6.2 Presentation Location of Haptic Stimuli

Throughout the thesis haptic stimuli where only presented to the glabrous side of the hand. While participants in Experiments 4 and 5 were free to hold their haptic comfort objects as they wished, it is unclear how affective responses to single-actuator emotionally resonant vibrotactile stimuli may vary at different bodily locations. Investigation of this would inform whether these stimuli could augment other objects, like wearable devices or seats, to provide emotionally resonant experiences.

6.6.3 Single Actuator Stimuli

Emotionally resonant vibrations were conveyed using a single vibrotactile actuator, a Haptuator Mark II. This allowed the development of stimuli which could augment the many existing devices which contain a vibrotactile actuator. More complicated haptic interfaces may have the potential to present more detailed and varied stimuli which leverage emotional resonance. During the research for this thesis, Shim *et al.* demonstrated the ability to craft vibrotactile stimuli evocative of certain real-world sensations using a 2x2 Tactor array [199]. Future work to effectively map the design possibilities for emotionally resonant haptic stimuli would be a valuable asset when creating new affective interfaces which can make use of more complex hardware.

6.6.4 Emotionally Resonant Vibrations in Other Contexts

This thesis developed emotionally resonant vibrotactile stimuli as an intervention to address the specific use case of social exposure for socially anxious users, motivated by the difficulty of adhering to exposure therapy. These stimuli were effective in evoking real-world sensations and participants' specific associated emotions with those sensations. Aside from their potential utility as a social anxiety intervention, other applications can be hypothesised, such as presenting emotionally resonant cues alongside matching visual or auditory stimuli to create immersive multimodal experiences. It would be valuable for future work to explore how to utilise these stimuli in the creation or improvement of affective interfaces.

6.6.5 Integrating Thermotactile Cues into Comfort Objects

During this research the use of thermotactile stimuli in personalised comfort objects was not pursued following a trial in Experiment 3. This was because, despite the ability for thermal cues to enhance the emotional resonance and affective range of some emotionally resonant vibrations, the size of this effect was too small to justify the practical restrictions placed on comfort object design by including the bulky Peltier unit available which conveys temperature through one small square element. There is, however, still value in exploring using thermal cues alongside emotionally resonant haptic comfort objects to enhance their effectiveness. Future research could pursue this aim utilising either smaller and more flexible thermotactile actuators, or bespoke comfort objects specifically designed to accommodate larger elements.

6.6.6 In-the-Wild Use of Haptic Comfort Objects

This thesis put emphasis on leveraging the personal preferences of socially anxious users in the development of haptic comfort objects as a social exposure intervention. The use of these comfort objects was only observed, however, in laboratory settings. Observation of in-the-wild interactions with emotionally resonant haptic comfort objects would yield insight into if these comfort objects enable emotion regulation in different real-world scenarios and if, when and why participants choose to make use them.

6.6.7 Participant Demographics

Participants were biased toward a younger age range of 20-30 years and largely recruited through university channels. Additionally, four of the five studies had 20 participants and the final between-groups study had 14 participants per group. This was a practical limitation of recruiting socially anxious participants and was worsened by the COVID-19 pandemic. Investigation of affective responses to emotionally resonant vibrations, or observation of socially anxious users experiences and haptic preferences, across a more diverse set of participants would inform how applicable these findings are over larger populations.

6.6.8 Specific Applicability to Exposure Therapy

The initial focus of this thesis was to find a way to specifically ease adherence to exposure therapy, allowing the work to directly aim to support a solution for social anxiety. In order to properly assess the impact of the intervention in exposure therapy, however, it would ideally need to be integrated into exposure therapy programs, alongside therapists and patients. In practicality, however, as the research progressed it focused more of generally making social exposure easier or less difficult. This lead to the project being more widely applicable, as social exposure is a core component of many societal interactions and public spaces, but less applicable to supporting specifically exposure therapy, which I would now view more as one compelling use case to specifically explored in future, as described above.

6.6.9 Individual Differences

Throughout this research the individualistic nature of participant responses to emotionally resonant stimuli is often noted, and provided as an explanation for the varied responses found from Experiment 2 to Experiment 4. Despite this, we did not conduct explore how individual differences or experiences may systematically impact said preferences. Future work could investigate this in different ways. The potential impact of individual personality traits could be assessed using frameworks such as the Big 5 [44], which places people on 5 personality axis: conscientiousness, neuroticism, extroversion, openness and agreeableness [115]. Given the trend of participants linking their perceived emotional resonance of stimuli to past experiences, however, it may be more important to instead investigate the individual differences in prior affective experience. Capturing life experiences such that they could be meaningful compared between participants may, however, prove challenging. One within-participants approach to investigate this could be to observe a participant's emotional responses to a base stimuli set, similarly to the set used in this work, and then conduct long-form personalisation and customisation with that participant and compare later emotional responses, to see if this tailoring process around personal experiences had a significant impact.

6.6.10 Social Desirability Bias

Throughout this thesis, participants were often asked to give feedback on the emotionally resonant vibrations and comfort objects they experienced. This was extremely valuable in understanding why certain stimuli performed better than others, participants prototyped or chose certain comfort objects, and how they felt they were impacted by these interventions. While feedback on this intervention was largely very positive, all of this must be taken in the context of *social desirability bias*, which describes an effect whereby respondents will answer questions in more acceptable or socially agreeable way. In this case, this could have caused participants to over-represent their positive impressions of the intervention and downplay their negative impressions. This effect may be particularly pronounced in socially anxious participants, who wish to avoid their actions resulting an a negative response or conflict. While this is a innate limitation of these research techniques, it motivates future longitudinal observation of the use of emotionally resonant vibrotactile comfort objects, to better establish if the positive feedback regarding the calming nature of usefulness of the intervention bore out in real use.

6.6.11 Impact of the COVID-19 Pandemic

The bulk of research undertaken during this thesis took place during the heights of the COVID-19 pandemic, and this provided both significant challenges and several lessons to learn. First, there was a shortage of opportunities between lockdown periods during which in-person studies, especially those which relied on touching surfaces, were allowable or advisable. This naturally led to a changes in scope and approach. Participatory prototyping was originally planned as a focus group, but conducting such an activity with socially anxious people presented a ethical concerns about inducing distress in participants. While this concern was being explored the restrictions of COVID-19 came into effect making focus groups even more problematic, prompting the switch to one-person prototyping sessions. Additionally, initially it was planned to run the prototyping sessions in an iterative manner with the same participants, allowing comfort objects to be more closely shaped by their preferences and experiences. These iterated prototypes could then have been assessed with their creators in a final exposure task. COVID-19 also impacted said exposure task, as in-person audiences with multiple members become unsafe. The procedure was instead swapped to non-standard online presentation approach, which then needed to be validated to show it still evoked a significant increase anxious responses. Recruitment also proved challenging in this period which especially impacted a between-groups study.

6.7 Conclusions

Social anxiety is one of the world's most prominent mental health issues and negatively impacts quality of life. Social exposure therapy is a core component of psycho-therapeutic interventions for social anxiety, but facing one's fears in social situations is challenging and limits accessibility. This thesis details the development of a novel category of haptic cue intended to serve as a calming intervention that helps socially anxious users to regulate their anxiety response during exposure therapy. These emotionally resonant vibrotactile stimuli, which evoke real-world phenomena, were found to elicit more varied and meaningful emotional responses from users than prior vibrotactile research, although responses to each stimulus varied greatly between individuals. Participatory prototyping was then conducted to observe the preferences of socially anxious users for form-factor and texture, informing the design of a set of comfort objects which emotionally resonant stimuli could augment. The intervention was then evaluated following a personalisation approach. Socially anxious participants in a treatment group choose their preferred form factor, texture and emotionally resonant stimulus, then held the resultant haptic comfort object during a 3 minute social exposure task. When compared to participants in a control group, no significant change in anxiety symptoms was observed. Treatment group participants had a much wider distribution of physiological anxiety scores, which may suggest that the comfort objects had an effect on some, but not all, participants' perception of their anxiety symptoms. Emotionally resonant haptic comfort objects could be a useful emotion regulation tool for some users on a case-by-case basis, a hypothesis further supported by overwhelming participant feedback that the comfort objects were calming to hold and could be helpful in future social scenarios, but are not an effective intervention for all users or addressing physical anxiety symptoms. This thesis contributes a novel category of vibrotactile cue, which can enable new emotional and meaningful experiences, and provides foundational knowledge of the specific requirements and preferences that socially anxious users have for affective haptic interfaces.

Appendix A

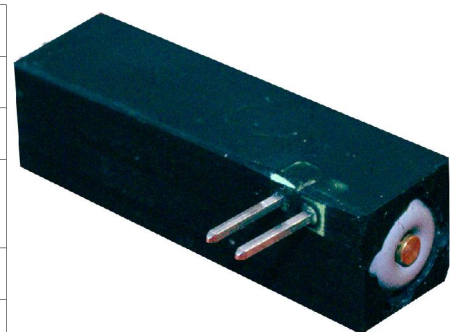
Hardware Manuals and Psychological Scales

A.1 Haptuator Mark II Specification

Haptuator Mark II

The *Haptuator Mark II* is a variation of the original Haptuator with a larger rated bandwidth, a higher acceleration output while being smaller in size. Like the original *Haptuator*, it also can be driven as a common loudspeaker and is compatible with most audio amplifiers.

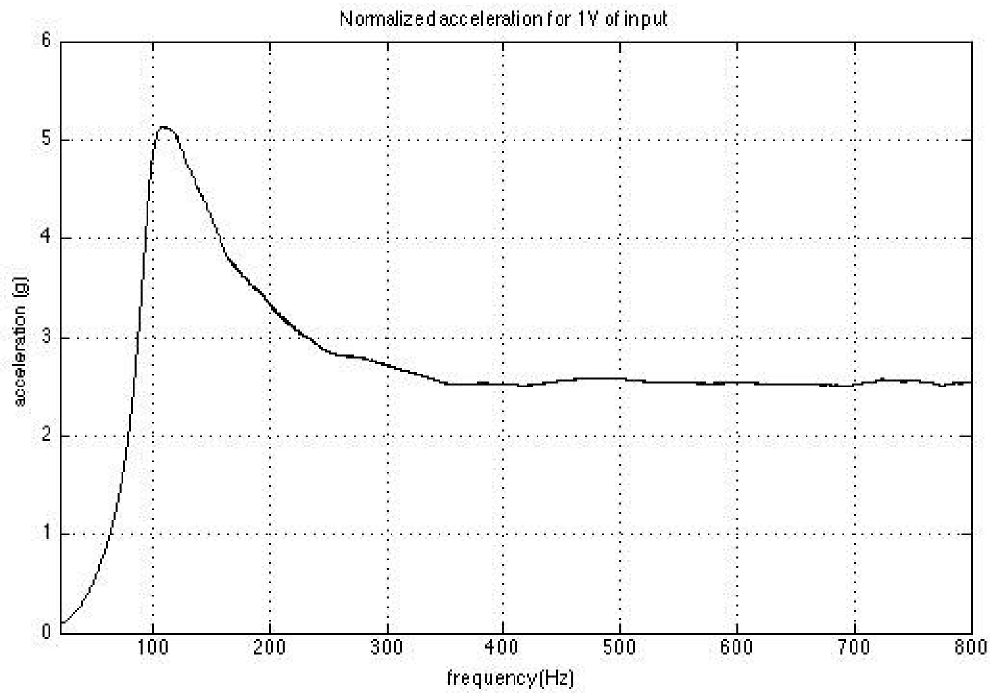
Model Number	TL002-09-A	
Outer Dimension	32 x 9 x 9	mm
Weight	9.5	grams
Acceleration @ 3V input, 125 Hz	7.5 73	G m/s^2
Rated Bandwidth	90 - 1000	Hz
Typical Impedance	5.5	Ω
Maximum Input Voltage	3.0	V
Maximum Input Current	0.5	A



TL002-09-A

Tel: 1 450-283-6148 Fax: 1-800-820-5789
info@tactilelabs.com www.tactilelabs.com

Output Acceleration



To calculated the output acceleration for a given input voltage of ***Vi*** (rms):

1. For the desired operating frequency, find the normalized acceleration value ***An*** from the above figure. For example, at 300 Hz, ***An*** = 2.7g.

2. Perform the following calculation:

$$Acceleration(G)=Vi \times An.$$

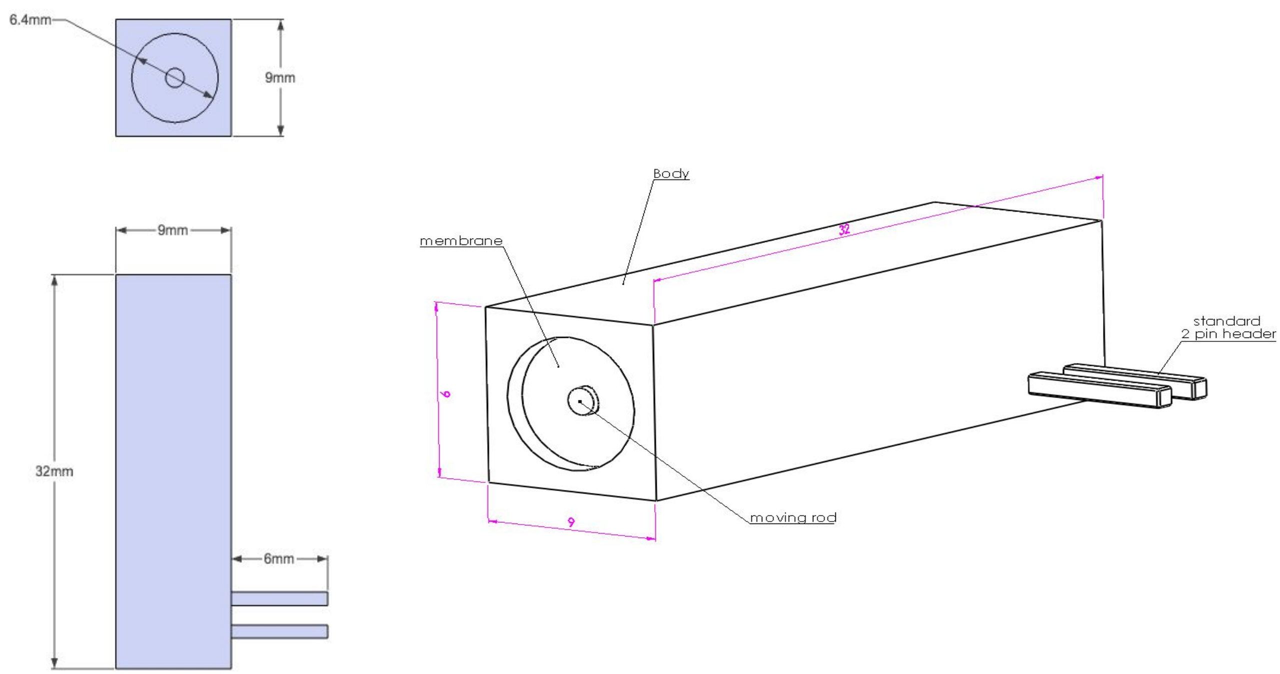
Notes:

1. The Haptuator Mark II can be driven as a 4-8 Ω loudspeaker by most audio amplifiers if the input current and voltage are within the recommended operating conditions. The Haptuator Mark should be AC-coupled to avoid driving a DC current into the unit.

2. It is not recommended to drive the Haptuator under 50Hz: the output acceleration would not be optimal. Driving at a minimum of 10 Hz or above 1000 Hz should not damage the actuator. However, for frequencies above 500 Hz, the signal output becomes audible, hence not as optimal for haptic applications.

Mechanical Dimensions

it is recommended to leave a 2mm clearance at both end of the Haptuator unit due to the movement of the internal assembly.

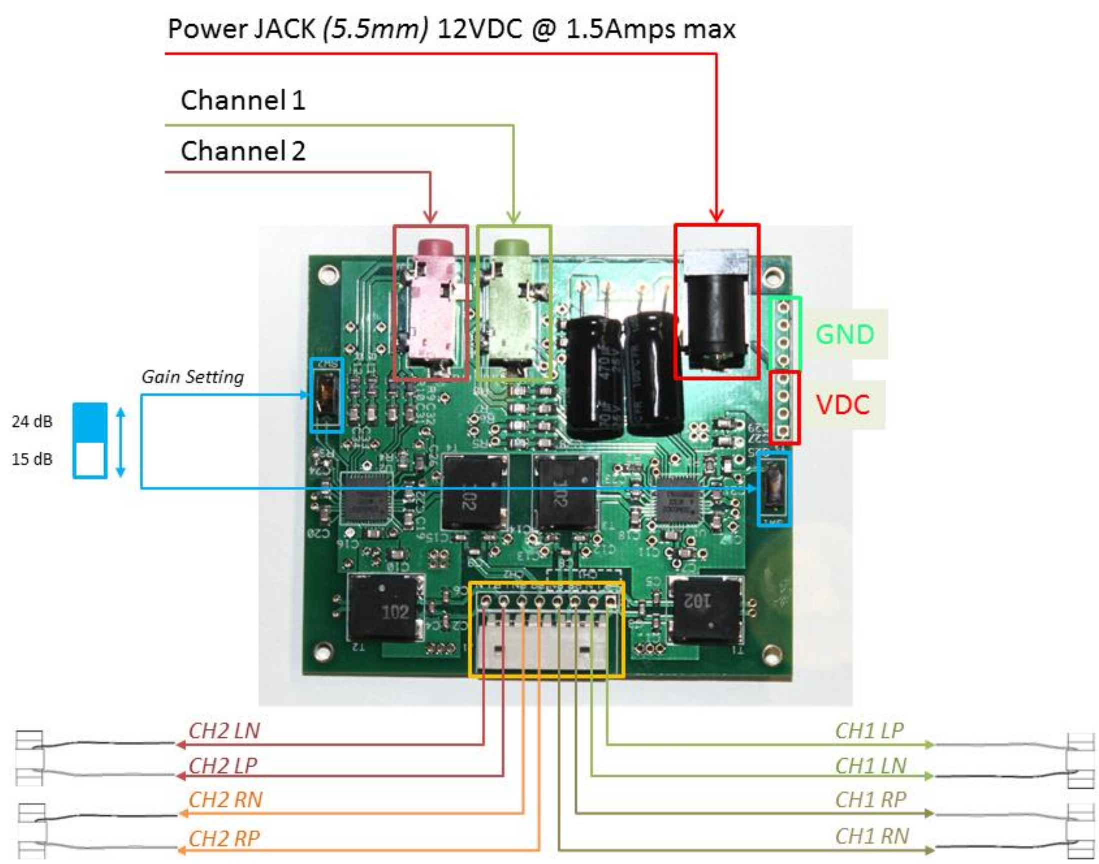


A.2 HaptuQuadAmp Board Specification

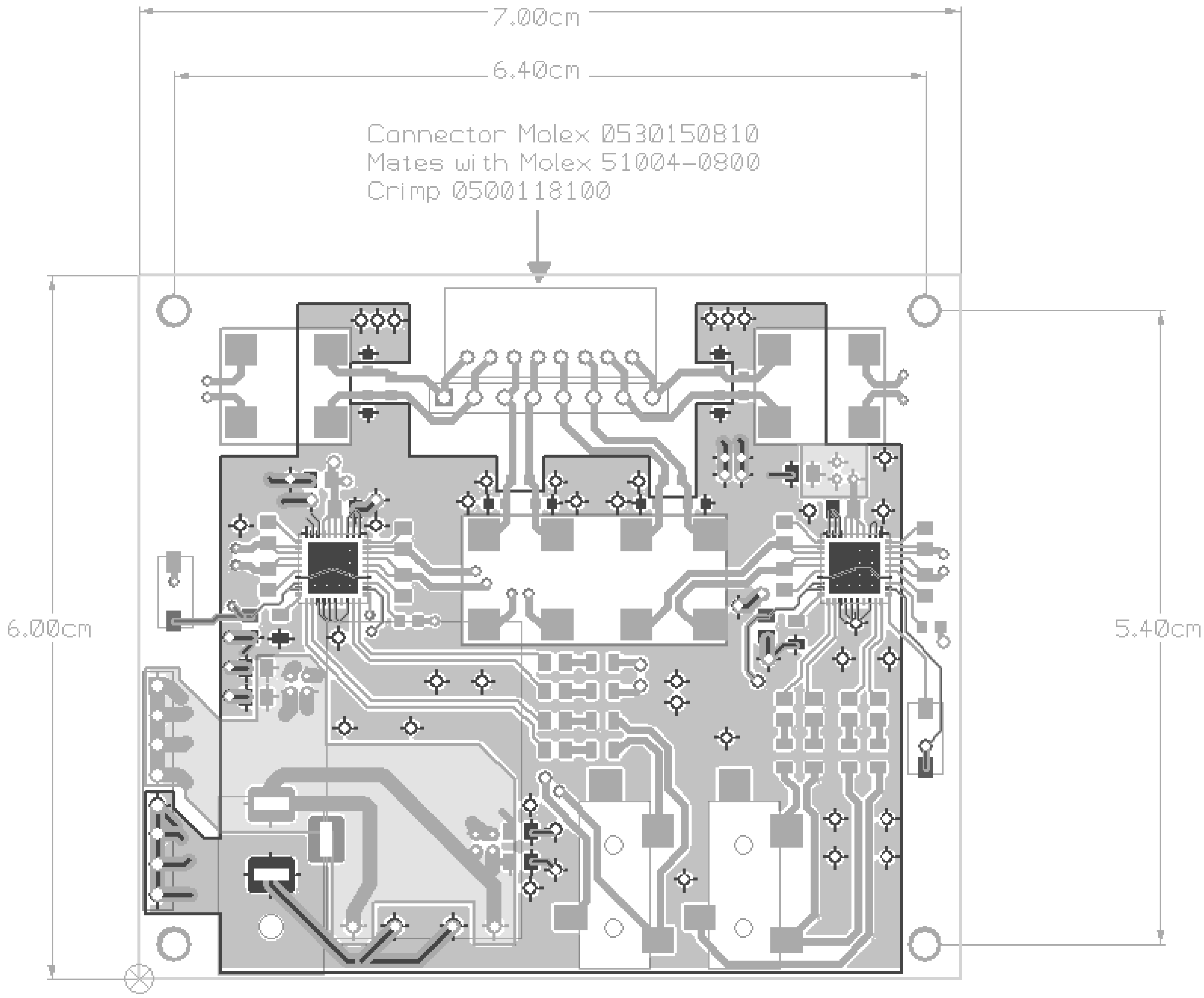
Multi-Channel Amplifier for Haptuator

(TL002-HaptuQuadAmp)

- >90% efficiency at 12 V, 8 W into Haptuators, can drive up to 12W into an Haptuator with < 1% THD (some restrictions apply)
- Single-supply operation from 7 V to 18 V
- High and low gain via a DIP-switch. Up to 24 dB of gain
- Short-circuit and thermal protection
- Molex Pico-Blade output connector for up to 4 Haptuators connectivity
- Four channel inputs via 2 stereo jack



TactileLabs



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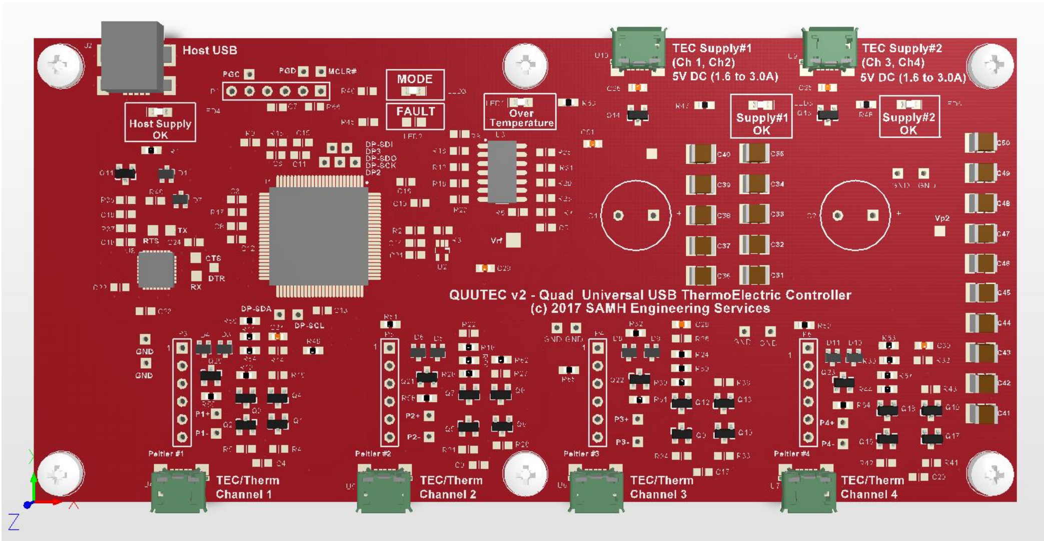
www.tactilelabs.com

A.3 QUUTEC - Quad Universal USB ThermoElectric Controller

QUUTEC
Quad Universal USB ThermoElectric Controller - User Manual Version 0.1 (Draft)



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Note: This hardware is for research purposes only

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Operational Overview:

The QUUTEC device allows up to 4 Peltier heat pump devices to be driven in either direction (hot or cold). Each channel has a temperature sensor which is used to close a PID feedback loop. Each channel can have its temperature set point adjusted on the fly by sending simple commands over a serial interface (via USB). The maximum range over which the temperature can be set is from -20degC to +45degC. The temperature for each channel can also be read back using similar commands. The drive electronics can source up to about 5W of power per channel – the recommended minimum load resistance of the Peltier devices is 3.5 ohms and they should be rated for 5V or more. The PID loop in the firmware has been tuned and tested when using the CP20251 heat pump from CUI INC.

As a safety mechanism there is dedicated electronics that are separate to the microcontroller to monitor the temperature of each channel. If the temperature rises above about 60 degrees Celsius on any channel this circuit will shut down all power to the Peltier heat pumps. This ensures that in the event of the microcontroller 'crashing' a situation that could cause burns will not arise.

Additionally the microcontroller implements safety mechanisms that will shut off power to the heat pumps if their temperature rises above 50 degC under normal operation. It will also shut off the heat pumps if the thermistor that senses the temperature of an active channel becomes electrically disconnected.

Furthermore, in the event that the thermistor becomes detached from the surface of a heat pump of which it is supposed to be sensing, then the heat pump will be shut down 12 seconds after the detachment.

Note: It is important that the thermistor remains properly bonded to the exposed surface of the heat pump. Super-glue is sufficient for this purpose once the ceramic surface of the heat pump has been roughened with sand paper. If the thermistor becomes detached from the heat pump surface there is a danger that the temperature could reach 70 degrees C for a second or two before the detached thermistor protection mechanism kicks in.

The circuit and firmware have been designed and written to support a thermistor with the following characteristics:

- Resistance in Ohms @ 25°C 10k
- Resistance Tolerance ±1%
- B Value Tolerance ±1%
- B25/50 3375K +/- 5K
- B25/85 3435K +/- 5K

For example, the following thermistors can be used:

- Panasonic - ERT-J0EG103FA
- Murata - NXFT15XH103FA1B025

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Thermistors with characteristics other than those listed above are not supported by this hardware.

Normally the thermistor will be placed close to an edge of the exposed surface of the heat pump. For correct operation of a temperature display to a person's finger it is important that the finger is not placed on top of the thermistor as this will distort the temperature reading from the surface.

The steady state error between the set point and actual channel temperature is typically less than 1degC. Step changes of large magnitude (20 degrees) can result in overshoot of about 2 degC before settling to the set point temperature. The rate of change of temperature of the surface of the heat pump is typically 3 degrees C / second, however this can be limited to about 1 degree C / second as described in the Modify Rate of Change Limit Command section below.

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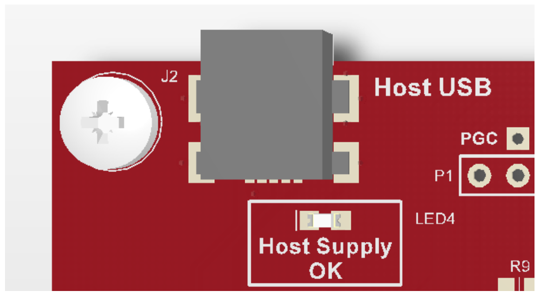
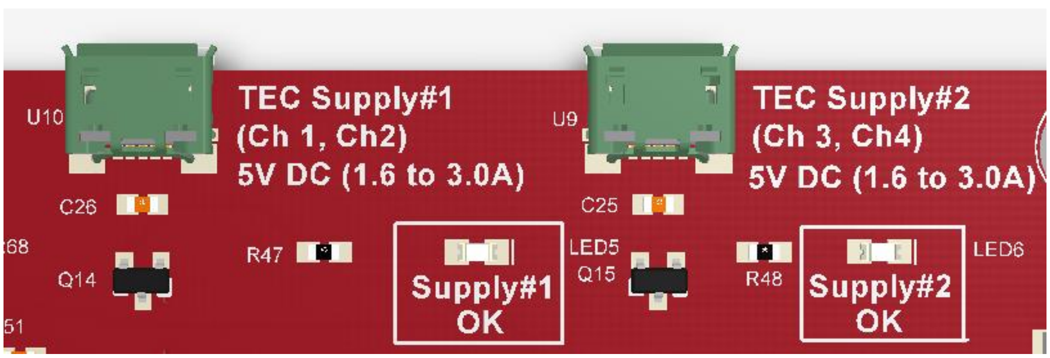
Device Connections and Setup:

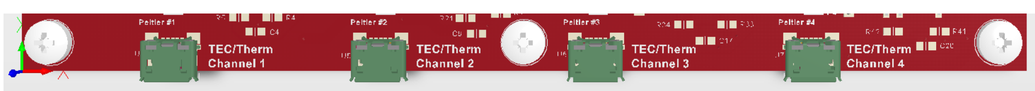
The QUUTEC device is designed to connect to a host PC using a USB cable (mini-B plug) connected to the "Host USB" socket:



The device obtains power for the Peltiers from 5V power supplies with a micro-USB plug and with 1.6A or greater output capability (recommended minimum is 2A). They connect to the sockets shown here:



The Peltier heat pumps and their temperature sensing thermistors are supplied individually, attached to heat sinks. They are connected to the device via the 4 micro-USB sockets on the front of the PCB:



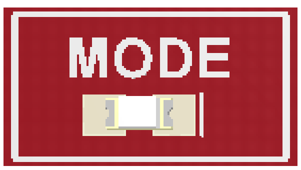
Programming / Communication Reference:

The device includes a microcontroller that responds to commands originating from a connected (host) computer. This host communicates with the device via a serial COM port over a USB physical interface.

The USB interface is based on the FT232R IC and drivers can be downloaded here - http://www.ftdichip.com/Drivers/VCP.htm.

The COM port settings are BAUD = 460800, 1 start bit, 8 data bits, 1 stop bit, no parity and hardware flow control.

When the COM port is opened, the MODE LED on the device should illuminate green, and when the COM port is closed, the MODE LED should extinguish.



The host configures the device by sending command packets, and the device will return acknowledge packets with the result if the command executed successfully and not-acknowledge packets if the command was not executed.

Note: reasons that a command may not execute is that a previous command has not completed execution, or the command argument or type are invalid.

The device will also send back event packets in the event that a fault condition was detected (either an over temperature fault or a supply brown out fault).

All command packets to the device have the following format -

`$CMD,tttt,cc`

where `tttt` is the command argument (a 16 bit signed integer)
and `cc` is the command type (an 8 bit unsigned integer)
and the format is in Hex.

A detailed description for each command are listed at the end of this document with several examples cited for clarity.

The acknowledge packet returned by the device to the hosts always takes this format –

`$ACK,tttt,cc`

where `tttt` is the acknowledge value (a 16 bit signed integer)
and `cc` is the command type that owns this acknowledge (an 8 bit unsigned integer)
and the format is in Hex.

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Finally, a not-acknowledge packet takes this format -

```
$NAK,tttt,cc
```

where `tttt` is 0000
and `cc` is the command type that caused this not-acknowledge (an 8 bit unsigned integer) and the format is in Hexadecimal.

When the host first opens the COM port to the device, it will receive the following text (note that the firmware revision numbers may be different to that printed here) –

```
QUUTEC Quad Universal USB Thermoelectric Controller v2.00
Copyright 2017 SAMH Engineering Services
Firmware Revision 00.00
```

where the firmware revision will vary but always have the format AA.bb where A and b are decimal digits.

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Device Reset Command

In the event of an error condition, or to immediately disable all heat pumps, the reset command can be invoked by sending a '!' character (ASCII code 33).

Once received, the device will
- Reset the previous error condition, if any
- Output the startup splash (see above)
- Revert all heat pump drivers to the OFF state

Set Temperature Command

This command is used to set the temperature of channel X where X is either 1,2 3 or 4 depending on which channel the temperature setpoint is to be configured.

The command argument field is signed 16 bit integer in units of tenths of a degree Celsius. The maximum range over which the temperature can be set is from -20degC to +45degC.

The command type has the value of the channel number to read.

Example:
To set the temperature of channel 1 to 45 degreesC send this command –

```
$CMD,01C2,01
```

To set the temperature of channel 4 to 0 degreesC send this command –

```
$CMD,0000,04
```

To set the temperature of channel 2 to -20 degreesC send this command –

```
$CMD,FF38,02
```

To disable a channel, set the value field to 0xFFFF. For example to disable channels 3 and 4 send –

```
$CMD,FFFF,03
$CMD,FFFF,04
```

Note: In practice, it may not be possible for the temperature delta between ambient and the surface of the Peltier to exceed a magnitude of 20 deg C. For example, if the ambient temperature is 25 deg C, it may only be possible for the Peltier to drive the temperature to 5 deg C, due to the power constraints of the Peltier modules and the heatsinking ability of the heatsink to which the Peltier is attached.

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Read Temperature Command

This command is used to read the temperature of channel x where x is either 1,2 3 or 4 depending on which channel you want to set the temperature for.

The command type has the value 0x05, and the command argument is the channel number to read.

The temperature is returned in the value field of an $ACK packet. It is in hex format, signed 16 bit, and units of tenths of a degree Celsius.

Example:
To read the temperature of channel 1 send this command –

```
$CMD,0001,05
```

If the temperature is 20 degrees C, then the returned packet is –

```
$ACK,00CB,05
```

Example:
To read the temperature of channel 4 send this command –

```
$CMD,0004,05
```

If the temperature is 20 degrees C, then the returned packet is –

```
$ACK,00CB,05
```

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Read Temperature Setpoint Command

This command is used to read the temperature set-point of any one of the 4 channels.

The command type has the value 0x06, and the command argument is the channel number to read.

The temperature is returned in the value field of an $ACK packet. It is in hex format, signed 16 bit, and units of tenths of a degree Celsius.

Example:
To read the temperature set-point of channel 1 send this command –

```
$CMD,0001,06
```

If the temperature set-point is 20 degrees C then the returned packet is –

```
$ACK,00CB,06
```

The default set-point temperatures after power up is the value 0xFFFF which implies that the channel is disabled.

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Modify Rate of Change Limit Command

Use this command to enable or disable the limiting of the rate of change of temperature to the heat pumps. Normally the rate of change can be up to 3 degrees/second with the specified Peltiers, but in certain circumstances this rate of change may need to be reduced. If the limit is enabled, the maximum rate will typically be reduced by a factor of three to about 1 degree per second, although variations will manifest depending on the Peltiers used and the starting and ending temperature during the change.

The command type has the value 0x08, and the command argument is-

DISABLE_RATE_LIMIT = 0x0000,
ENABLE_RATE_LIMIT = 0x0001

If successful, an ACK packet will be returned with 8 as its first argument and the CMD_SET_ROC_LIMIT enumeration code as the second argument.

Example: To set the rate limit for all 4 channels to 1 degree per second send this command –

```
$CMD,0001,08
```

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Data Streaming:

For debugging purposes it is possible to enable streaming of the current temperature and set point temperatures for all channels. The temperatures are output in units of degrees Celsius.

To disable this feature send the following command –

```
$CMD,0000,07
```

To re-enable it send this command –

```
$CMD,0001,07
```

This feature is **enabled** by default.

The following is typical of the output data, and it is output a couple of times per second -

```
$SET POINT  ,+20,+20,###,###
$TEMPERATURE,+21,+19,+21,+20
```

Note: If the temperature setpoint has not been configured for a channel, the set point shall be listed as ###. This indicates that this particular channel is disabled, i.e. no heating or cooling is active for that channel.

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Fault Events:

There are four circumstances that can cause a fault event -

1) If any one of the active channels has an over temperature condition
2) If the temperature sense thermistor for any active channel is electrically disconnected
3) If the thermistor for any active channel becomes detached from the heat pump and if that heat pump is driven in the hot direction for more than about 12 seconds
4) If there is a brown out on the supply voltage (when supplied from a power supply) or if the battery is low (when supplied with the battery pack)

In this circumstance the following packet will be output -

```
$EVT,000X,00
```

Where X is the fault reason number.

- 1 – Over Temperature Fault
- 2 – Disconnected Thermistor Fault
- 3 – Detached Thermistor Fault
- 4 – Brown-out Fault

The device will also shut down to a low power state and indicate a flashing pattern on the FAULT LED.

This pattern is a long flash followed by a series of short flashes where the number of short flashes is the same as the number of the fault event as listed above.

In order to recover from a fault condition either

- Sending a reset command (i.e. by sending the '!' character, see Reset Command section above).
- the power to the device must be cycled by removing then re-inserting the host USB cable

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Firmware Upgrade:

To perform a firmware upgrade:

1. unzip the .exe and .hex firmware files to a folder on a windows PC.

QUUTEC Firmware Upgrade Tool.exe	28/02/2017 11:24	Application	13 KB
QUUTEC.hex	28/02/2017 11:28	UltraEdit Docume...	70 KB

2. Make a note of the COM port number that the device is normally connected to the PC.

3. Disconnect the power and USB cables from the device.

4. Run the QUUTEC Firmware Upgrade Tool.exe program.

5. Follow the instructions displayed.

6. Wait until the bootloader program has finished execution, then re-connect and use the device as normal.

C:\del\0.01 test\QUUTEC Firmware Upgrade Tool.exe

```
QUUTEC Quad Universal USB ThermoElectric Controller
(c)2017 SAMH Engineering Services

Opened hex file: QUUTEC.hex
Please Disconnect the USB and power cable from the QUUTEC deviec to be updated.
Press any key to continue . . .

Please reconnect the Host USB cable - ensure that the red LED illuminates.
Press any key to continue . . .

Please Enter the COM port number that the device is connectable on : 87


Connect USB cable to device now...
Waiting for COM port #87 to open
COM Port 87 opened..Found target microcontroller.
Succesfully connected to the QUUTEC device.
.
Programming Device .................................................................
 Done.

Firmware Upgraded Succesfully
Press any key to continue . . . _
```

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Document History

Revision #	Date	Changes
0.1	27/02/2017	Initial Draft

A.4 SIAS - Social Interaction Anxiety Scale

Social Interaction Anxiety Scale (SIAS)

Patient Name: ______________________ **Date:** ____________

Instructions: For each item, please circle the number to indicate the degree to which you feel the statement is characteristic or true for you. The rating scale is as follows:

0 = **Not at all** characteristic or true of me.
1 = **Slightly** characteristic or true of me.
2 = **Moderately** characteristic or true of me.
3 = **Very** characteristic or true of me.
4 = **Extremely** characteristic or true of me.

CHARACTERISTIC	NOT AT ALL	SLIGHTLY	MODERATELY	VERY	EXTREMELY
1. I get nervous if I have to speak with someone in authority (teacher, boss, etc.).	0	1	2	3	4
2. I have difficulty making eye contact with others.	0	1	2	3	4
3. I become tense if I have to talk about myself or my feelings.	0	1	2	3	4
4. I find it difficult to mix comfortably with the people I work with.	0	1	2	3	4
5. I find it easy to make friends my own age.	0	1	2	3	4
6. I tense up if I meet an acquaintance in the street.	0	1	2	3	4
7. When mixing socially, I am uncomfortable.	0	1	2	3	4
8. I feel tense if I am alone with just one other person.	0	1	2	3	4
9. I am at ease meeting people at parties, etc.	0	1	2	3	4
10. I have difficulty talking with other people.	0	1	2	3	4
11. I find it easy to think of things to talk about.	0	1	2	3	4
12. I worry about expressing myself in case I appear awkward.	0	1	2	3	4
13. I find it difficult to disagree with another's point of view.	0	1	2	3	4
14. I have difficulty talking to attractive persons of the opposite sex.	0	1	2	3	4
15. I find myself worrying that I won't know what to say in social situations.	0	1	2	3	4
16. I am nervous mixing with people I don't know well.	0	1	2	3	4
17. I feel I'll say something embarrassing when talking.	0	1	2	3	4
18. When mixing in a group, I find myself worrying I will be ignored.	0	1	2	3	4
19. I am tense mixing in a group.	0	1	2	3	4
20. I am unsure whether to greet someone I know only slightly.	0	1	2	3	4

A.5 STAI - State-Trait Anxiety Inventory for Adults

Sample Item Letter

mind garden

www.mindgarden.com

To whom it may concern,

This letter is to grant permission for the above named person to use the following copyright material for his/her thesis or dissertation research;

Instrument:

Authors:

Copyright:

Five sample items from this instrument may be reproduced for inclusion in a proposal, thesis, or dissertation.

The entire instrument may not be included or reproduced at any time in any other published material.

State-Trait Anxiety Inventory for Adults

Self-Evaluation Questionnaire

STAI Form Y-1 and Form Y-2

Developed by Charles D. Spielberger
in collaboration with R.L. Gorsuch, R. Lushene, P.R. Vagg, and G.A. Jacobs

Distributed by Mind Garden, Inc.

info@mindgarden.com
www.mindgarden.com

Note to Masters and Doctoral Students:
You may insert the following SAMPLE copy of the instrument in your IRB proposal if necessary.
You may NOT insert a complete copy of the instrument in your Thesis or Dissertation!!!
See Mind Garden Sample Item letter for details.

SELF-EVALUATION QUESTIONNAIRE

STAI Form Y-1

Please provide the following information:

Name____Date______________S_____

Age___________________ Gender (*Circle*) **M** **F** T_____

DIRECTIONS:

A number of statements which people have used to describe themselves are given below. Read each statement and then blacken the appropriate circle to the right of the statement to indicate how you feel *right* now, that is, *at this moment*. There are no right or wrong answers. Do not spend too much time on any one statement but give the answer which seems to describe your present feelings best.

	NOT AT ALL	SOMEWHAT	MODERATELY SO	VERY MUCH SO
1. I feel calm	**1**	**2**	**3**	**4**
2. I feel secure	**1**	**2**	**3**	**4**
3. I am tense	**1**	**2**	**3**	**4**
4. I feel strained	**1**	**2**	**3**	**4**
5. I feel at ease	**1**	**2**	**3**	**4**
6. I feel upset	**1**	**2**	**3**	**4**
7. I am presently worrying over possible misfortunes	**1**	**2**	**3**	**4**
8. I feel satisfied	**1**	**2**	**3**	**4**
9. I feel frightened	**1**	**2**	**3**	**4**
10. I feel comfortable	**1**	**2**	**3**	**4**
11. I feel self-confident	**1**	**2**	**3**	**4**
12. I feel nervous	**1**	**2**	**3**	**4**
13. I am jittery	**1**	**2**	**3**	**4**
14. I feel indecisive	**1**	**2**	**3**	**4**
15. I am relaxed	**1**	**2**	**3**	**4**
16. I feel content	**1**	**2**	**3**	**4**
17. I am worried	**1**	**2**	**3**	**4**
18. I feel confused	**1**	**2**	**3**	**4**
19. I feel steady	**1**	**2**	**3**	**4**
20. I feel pleasant	**1**	**2**	**3**	**4**

SELF-EVALUATION QUESTIONNAIRE

STAI Form Y-2

Name____Date_________

DIRECTIONS

A number of statements which people have used to describe themselves are given below. Read each statement and then blacken in the appropriate circle to the right of the statement to indicate you *generally* feel.

	ALMOST NEVER	SOMETIMES	OFTEN	ALMOST ALWAYS
21. I feel pleasant	**1**	**2**	**3**	**4**
22. I feel nervous and restless	**1**	**2**	**3**	**4**
23. I feel satisfied with myself	**1**	**2**	**3**	**4**
24. I wish I could be as happy as others seem to be	**1**	**2**	**3**	**4**
25. I feel like a failure	**1**	**2**	**3**	**4**
26. I feel rested	**1**	**2**	**3**	**4**
27. I am "calm, cool, and collected"	**1**	**2**	**3**	**4**
28. I feel that difficulties are piling up so that I cannot overcome them	**1**	**2**	**3**	**4**
29. I worry too much over something that really doesn't matter	**1**	**2**	**3**	**4**
30. I am happy	**1**	**2**	**3**	**4**
31. I have disturbing thoughts	**1**	**2**	**3**	**4**
32. I lack self-confidence	**1**	**2**	**3**	**4**
33. I feel secure	**1**	**2**	**3**	**4**
34. I make decisions easily	**1**	**2**	**3**	**4**
35. I feel inadequate	**1**	**2**	**3**	**4**
36. I am content	**1**	**2**	**3**	**4**
37. Some unimportant thought runs through my mind and bothers me	**1**	**2**	**3**	**4**
38. I take disappointments so keenly that I can't put them out of my mind	**1**	**2**	**3**	**4**
39. I am a steady person	**1**	**2**	**3**	**4**
40. I get in a state of tension or turmoil as I think over my recent concerns and interests	**1**	**2**	**3**	**4**

Appendix B

Study Materials

B.1 Experiment 1

B.1.1 Information Sheet

PARTICIPANT INFORMATION SHEET

Date: 07/02/2019

Title: Investigating the Effect of Duration on Vibrotactile Affective Touch

You are being invited to take part in a research study. 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.

Purpose of the study:

The purpose of the study is to investigate the emotional response that users have to untested vibrotactile stimulations delivered to their palms. The results can then be compared to previous studies to contrast the effect that changes in duration or waveform had on the user's emotional reaction.

Why have you been chosen:

You have been chosen because you are an adult and your health is in good condition.

Do I have to take part?

The participation in the study is voluntary. You may decide whether or not to take part. If you do decide to take part, you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part, you are still free to withdraw at any time and without giving a reason.

What will happen to me if I take part?

You will sit at a table, upon which are a laptop and the metal hand rest. You will rest your non-dominant hand on the palm rest, so that you can use your dominant hand to control the laptop with the mouse.

In Task 1, you will be presented one of 9 different vibrations through the hand rest. After each one you will be presented with a 2 popup windows on the laptop asking you to record how the stimulus made you feel. Once you finish with the second popup window, you will be presented with the next stimulus. This will repeat 9 times. After this there will then be a short break and then you will repeat this process, but the stimuli will be presented in a new random order.

In Task 2 you will repeat the process described in Task 1, but this time the vibrations you are presented with will be different. As before you will be presented with 9 total stimuli, allowed a short break, then presented with those 9 stimuli again in a new random order.

Once you have completed both tasks you will be asked to fill out a short survey about your experience and given the opportunity to ask any questions you may have before you finish.

What are the possible disadvantages and risks of taking part?

You could experience some mental fatigue while self-reflecting on how you feel after each stimulus. To help with this you will be in control of when you receive each new stimulus and allowed to take breaks if you wish.

What are the possible benefits of taking part?

You will be paid £6 for one hour of your time and you will have the chance to learn the outcomes of the following study.

Will my taking part in this study be kept confidential?

All information which collected, or responses provided, during the course of the research will be kept strictly confidential. You will be identified by an ID number which in no way will be able to be connected to you. Please note that assurances on confidentiality will be strictly adhered to unless evidence of serious harm, or risk of serious harm, is uncovered. In such cases the University may be obliged to contact relevant statutory bodies/agencies.

What will happen to the results of the research study?

The results will be held and owned by the researcher and the University of Glasgow. The results can be outlined to the participants whenever they become available. The participants won't be identified in any report or publication.

Who is organising and funding the research?

This research is funded by the School of Computing Science.

Who has reviewed the study?

The project has been reviewed by the College Ethics Committee.

Contact for Further Information:

You can contact the researcher of this study Shaun Macdonald via the following methods:

Email: s.macdonald.5@research.gla.ac.uk

Thank you for volunteering to take part in this study.

B.1.2 Consent Form

Investigating the Effects of Duration on Vibrotactile Affective Touch

CONSENT FORM

Before agreeing to this consent form, you should have been given an information sheet to read, which explains the general purpose of this study and the tasks it involves. If you did not receive this, please inform the experimenter. Throughout the study, the experimenter will explain in detail the different activities that you will be completing, but if you have any questions or require medical attention, please do not hesitate to ask.

In this study, you are required receive vibration stimuli on your non-dominant palm and record your reactions to them using a computer with your dominant hand. The systems you interact with will not ask personal information and all data is recorded anonymously. The data will be treated as confidential and kept in secure storage at all times. The material may be used in future academic research and publications, both print and online. The study will take approximately **60 minutes** to complete and **£6** will be paid at the end. If you are a student, **no course credits** will be awarded for completing this study. You can withdraw from the study at any time. Lastly, to take part in this study, the following criteria must be met:

- I am at least 18 years old.
- I have no sensory impairments in any of my hands.

Experimenter details: Mr Shaun Macdonald **(**s.macdonald.5@research.gla.ac.uk,)

Supervisor details: Professor Stephen Brewster (stephen.brewster.glasgow.gla.ac.uk, 0141-330-4966)

This study has been approved by the Ethics Committee (Reference Number Pending).

By signing this form, you have read the conditions stated above and agree to take part in the study.

FULL NAME: ____

SIGNATURE: ____

DATE: ____

EMAIL (if you want to be added to the participant's pool):

____

B.2 Experiment 2

B.2.1 Information Sheet

PARTICIPANT INFORMATION SHEET

Date: 07/07/2019

Title: Emotional Responses to Emotionally Resonant Vibrotactile Stimuli

You are being invited to take part in a research study. 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.

Purpose of the study:

This is an experiment to observe how people emotionally respond to certain vibrotactile stimuli. These stimuli have been generated using real-world sounds and tactile experience and will be simulated using a vibrating hand rest. The results will be used to help design new vibrotactile experiences in the future.

Why have you been chosen:

You have been chosen because you are an adult and your health is in good condition.

Do I have to take part?

The participation in the study is voluntary. You may decide whether or not to take part. If you do decide to take part, you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part, you are still free to withdraw at any time and without giving a reason.

What will happen to me if I take part?

You will sit at a table, upon which are a laptop and the metal hand rest. You will rest your non-dominant hand on the palm rest, so that you can use your dominant hand to control the laptop with the mouse.

In Task 1, you will be repeatedly presented 1 of 8 different vibrations in a random order through the hand rest. After each one you will be presented with 3 popup windows on the laptop asking you to record how the stimulus made you feel and if you could recognise that sensation being conveyed. Once you finish answering these questions you will be presented with the next stimulus.

In Task 2 you will repeat the process described in Task 1, but this time you will not be asked if you can recognise the stimuli presented. Instead the sensation being presented will be labelled at the top of each popup window. As before, you will be presented with these stimuli multiple times in a random order.

Once you have completed both tasks you will be asked to fill out a short survey about your experience and given the opportunity to ask any questions you may have before you finish.

What are the possible disadvantages and risks of taking part?

You could experience some mental fatigue while self-reflecting on how you feel after each stimulus. To help with this you will be in control of when you receive each new stimulus and allowed to take breaks if you wish.

What are the possible benefits of taking part?

You will be paid one £10 Amazon Voucher for up to one hour of your time and you will have the chance to learn the outcomes of the following study.

Will my taking part in this study be kept confidential?

All information which collected, or responses provided, during the course of the research will be kept strictly confidential. You will be identified by an ID number which in no way will be able to be connected to you. Please note that assurances on confidentiality will be strictly adhered to unless evidence of serious harm, or risk of serious harm, is uncovered. In such cases the University may be obliged to contact relevant statutory bodies/agencies.

What will happen to the results of the research study?

The results will be held and owned by the researcher and the University of Glasgow. The results can be outlined to the participants whenever they become available. The participants won't be identified in any report or publication.

Who is organising and funding the research?

This research is funded by the School of Computing Science.

Who has reviewed the study?

The project has been reviewed by the College Ethics Committee.

Contact for Further Information:

You can contact the researcher of this study Shaun Macdonald via the following methods:

Email: s.macdonald.5@research.gla.ac.uk

Thank you for volunteering to take part in this study.

B.2.2 Consent Form

Emotional Responses to Emotionally Resonant Vibrotactile Stimuli

CONSENT FORM

Before agreeing to this consent form, you should have been given an information sheet to read, which explains the general purpose of this study and the tasks it involves. If you did not receive this, please inform the experimenter. Throughout the study, the experimenter will explain in detail the different activities that you will be completing, but if you have any questions or require medical attention, please do not hesitate to ask.

In this study, you are required receive vibration stimuli on your non-dominant palm and record your reactions to them using a computer with your dominant hand. The systems you interact with will not ask personal information and all data is recorded anonymously. The data will be treated as confidential and kept in secure storage at all times. The material may be used in future academic research and publications, both print and online. The study will take appro**x**imately **40 minutes** to complete and an **£10** Amazon Voucher will be paid at the end. If you are a student, **no course credits** will be awarded for completing this study. You can withdraw from the study at any time. Lastly, to take part in this study, the following criteria must be met:

- I am at least 18 years old.
- I have no sensory impairments in any of my hands.

Experimenter details: Mr Shaun Macdonald **(**s.macdonald.5@research.gla.ac.uk,)

Supervisor details: Professor Stephen Brewster (stephen.brewster.glasgow.gla.ac.uk, 0141-330-4966)

This study has been approved by the Ethics Committee (Reference Number Pending).

By signing this form, you have read the conditions stated above and agree to take part in the study.

FULL NAME: ____

SIGNATURE: ____

DATE: ____

EMAIL (if you want to be added to the participant's pool):

____

University of Glasgow | School of Computing Science
GIST Glasgow Interactive Systems Group

B.3 Experiment 3

B.3.1 Information Sheet

PARTICIPANT INFORMATION SHEET

Date: 06/02/2020

Title: Measuring Emotional Response to Combining Vibration and Thermals

You are being invited to take part in a research study. 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.

Purpose of the study:

This is an experiment to observe how people emotionally respond to certain vibration stimuli, thermal stimuli, and combinations of both. The vibration stimuli have been generated using real-world sounds and tactile experiences while the thermal feedback will range from 24 to 34°C. The results will be used to help design new tactile experiences in the future.

What do I need to participate?

You can participate if you are over 18 in age, with your health in good condition and full sensory use of your hands.

Do I have to take part?

The participation in the study is voluntary. You may decide whether or not to take part. If you do decide to take part, you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part, you are still free to withdraw at any time and without giving a reason.

What will happen to me if I take part?

You will sit at a table, upon which are a laptop and the small box which will produce the thermal and vibration feedback. You will rest your non-dominant hand on the device, so that you can use your dominant hand to control the laptop with the mouse.

Before each task you will be given the option to try each stimulus and each combination of stimuli in a training phase to familiarise yourself with them.

In Task 1, you will be presented a variety of vibrations in a random order through the device. Each stimulus will last 10 seconds. After each one, you will be presented with 3 popup windows on the laptop asking you to record how the stimulus made you feel. Once you finish answering these questions you will be presented with the next stimulus. Once you have rated every stimulus you will take part in a short interview about how the stimuli felt to you and your experiences.

In Task 2 you will repeat the process described in Task 1, but this time you will experience thermal stimuli from the device instead. As before, once you have rated each stimulus presented there will be a short interview.

In Task 3 you will experience each possible combination of the thermal and vibration stimuli you felt in the first two tasks simultaneously for 10 seconds at a time.

Once you have completed all tasks you will be given the opportunity to ask any questions you may have before you finish. In total the experiment will take 50 minutes.

What are the possible disadvantages and risks of taking part?

You could experience some discomfort from the thermal feedback and vibration. To help with this you will be in control of when you receive each new stimulus and allowed to take breaks if you wish. If you find a certain stimulus very uncomfortable or painful you are also free to remove your hand from the device and inform the researcher.

What are the possible benefits of taking part?

You will be paid one £10 Amazon Voucher for up to one hour of your time and you will have the chance to learn the outcomes of the following study.

Will my taking part in this study be kept confidential?

All information which collected, or responses provided, during the course of the research will be kept strictly confidential. You will be identified by an ID number which in no way will be able to be connected to you. Please note that assurances on confidentiality will be strictly adhered to unless evidence of serious harm, or risk of serious harm, is uncovered. In such cases the University may be obliged to contact relevant statutory bodies/agencies.

What will happen to the results of the research study?

The results will be held and owned by the researcher and the University of Glasgow. The results can be outlined to the participants whenever they become available. The participants won't be identified in any report or publication.

Who is organising and funding the research?

This research is funded by the School of Computing Science.

Who has reviewed the study?

The project has been reviewed by the College Ethics Committee.

Contact for Further Information:

You can contact the researchers of this study, Shaun Macdonald and Stephen Brewster, via the following methods:

Shaun Macdonald Email: s.macdonald.5@research.gla.ac.uk

Stephen Brewster Email: stephen.brewster@glasgow.ac.uk

Thank you for volunteering to take part in this study.

B.3.2 Consent Form

Measuring Emotional Response to Combining Vibration and Thermals

CONSENT FORM

Before agreeing to this consent form, you should have been given an information sheet to read, which explains the general purpose of this study and the tasks it involves. If you did not receive this, please inform the experimenter. Throughout the study, the experimenter will explain in detail the different activities that you will be completing, but if you have any questions or require medical attention, please do not hesitate to ask.

In this study, you will receive vibration and thermal feedback on your non-dominant palm and record your reactions to them using a computer with your dominant hand. The systems you interact with will not ask personal information and all data is recorded anonymously. The data will be treated as confidential and kept in secure storage at all times. The material may be used in future academic research and publications, both print and online. The study will take approximately **50 minutes** to complete and an **£8** Amazon Voucher will be paid at the end. If you are a student, **no course credits** will be awarded for completing this study. You can withdraw from the study at any time. Lastly, to take part in this study, the following criteria must be met:

- I am at least 18 years old.
- I have no sensory impairments in any of my hands.

Experimenter details: Mr Shaun Macdonald **(**s.macdonald.5@research.gla.ac.uk,)

Supervisor details: Professor Stephen Brewster (stephen.brewster@glasgow.ac.uk, 0141-330-4966)

This study has been approved by the Ethics Committee (Reference Number Pending).

By signing this form, you have read the conditions stated above and agree to take part in the study.

FULL NAME: ____

SIGNATURE: ____

DATE: ____

EMAIL (if you want to be added to the participant's pool):

____

University of Glasgow | School of Computing Science

GIST Glasgow Interactive Systems Group

B.3.3 Stimuli Affective Responses Line Graphs

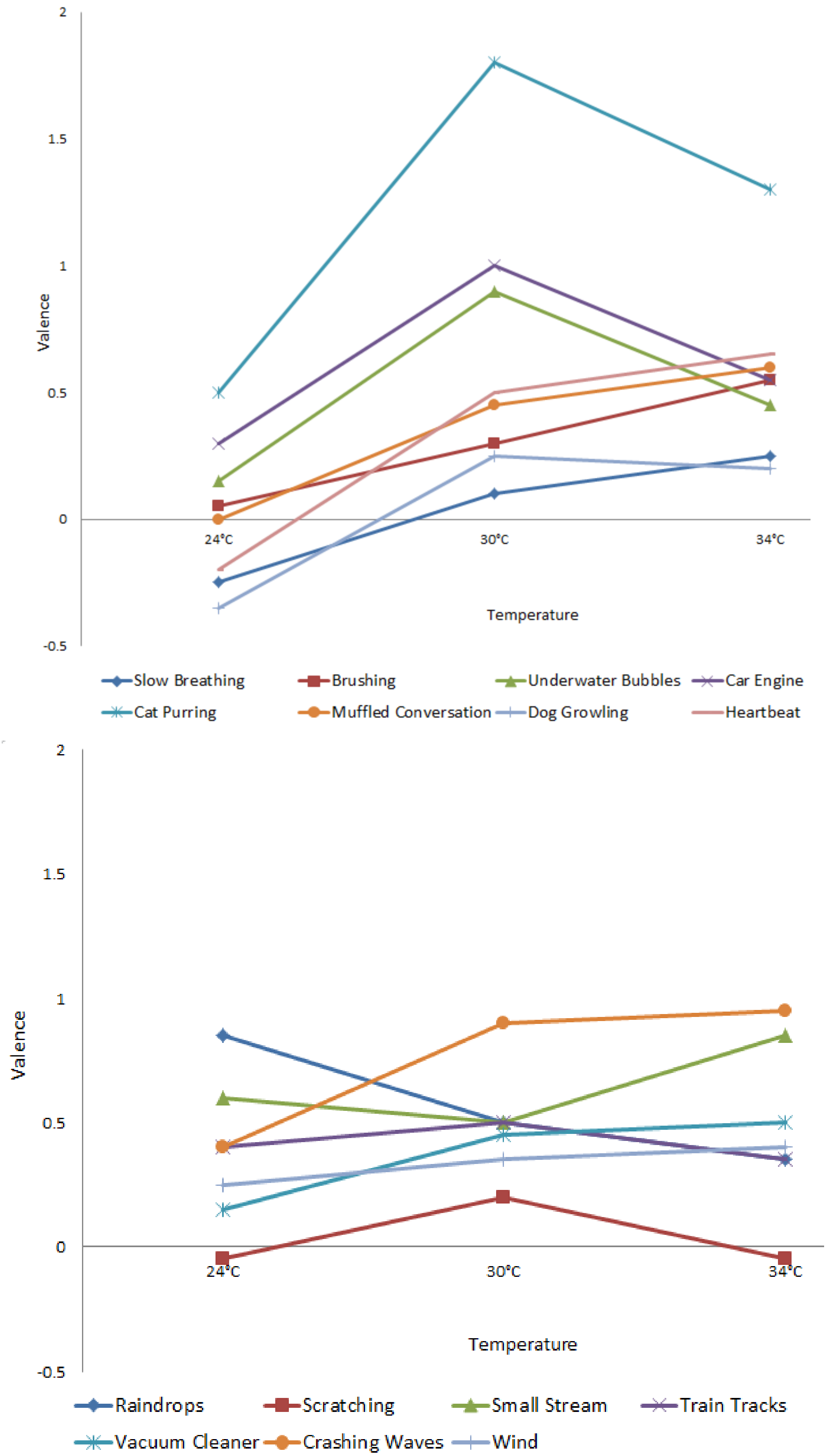

Figure B.1: Line plots showing mean valence responses for all fifteen emotionally resonant vibrotactile stimuli at all three temperature levels. Valence range of -0.5 to 2 is shown for clarity, from a total range of -3 to 3.

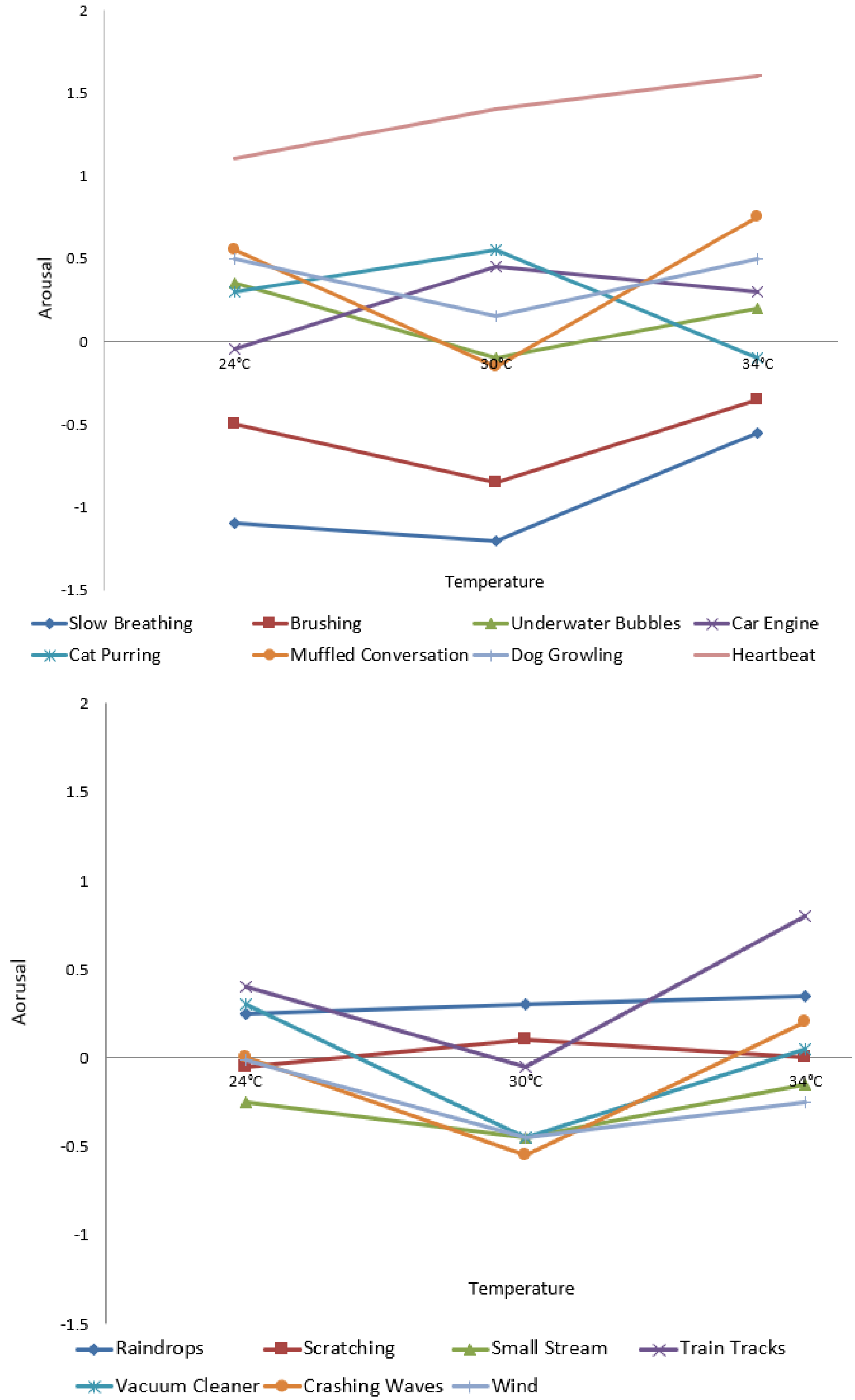

Figure B.2: Line plots showing mean arousal responses for all fifteen emotionally resonant vibrotactile stimuli at all three temperature levels. Arousal range of -1.5 to 2 is shown for clarity, from a total range of -3 to 3.

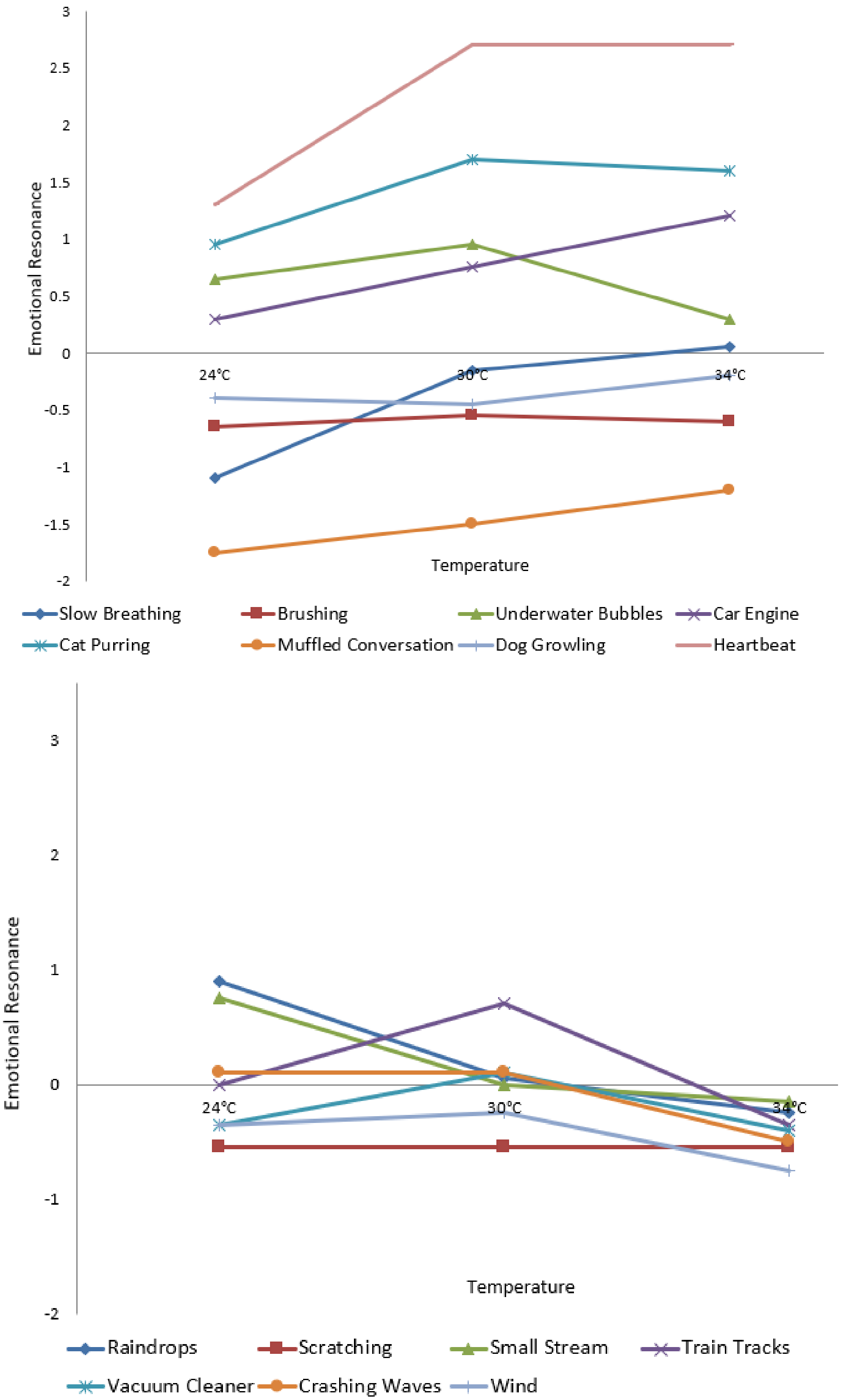

Figure B.3: Line plots showing mean emotional resonance responses for all fifteen emotionally resonant vibrotactile stimuli at all three temperature levels. Emotional resonance range of -2 to 3 is shown for clarity, from a total range of -3 to 3.

B.4 Survey 1

B.4.1 Information Sheet, Consent Form and Survey

Social Anxiety and Safety Behaviours

Page 1: Information Sheet

How Individuals Who Experience Social Anxiety Interact with Safety Behaviours and Affective Touch

You are being invited to take part in a research study. 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.

Purpose of the study:

The purpose of this study is to investigate how individuals who experience social anxiety utilise safety behaviours and experience emotional touch.
Safety behaviours are actions that an individual may intentionally or unintentionally use to reduce the impact of a situation they fear.
Emotional or affective touch sensations are touch sensations which communicate some emotion to an individual, or evoke emotion in them.
The results of this study's investigation will be used to shape the design of touch sensations designed to help calm and relax individuals during anxious periods, as well as better understand what coping mechanisms said individuals currently use.

Why have you been chosen:

You have been chosen because you are an adult who may have some experience of social anxiety. It does not matter whether or not you have been diagnosed or officially recognised as being socially anxious or if you consider yourself to be socially anxious. The first section of the survey will measure this.

Do I have to take part?

The participation in the study is voluntary. You may decide whether or not to take part. If you do decide to take part, you will be asked to fill out an online consent form. If you decide to take part, you are still free to withdraw at any time and without giving a reason.

What will happen to me if I take part?

You will be tasked with answering a survey with 3 main sections. The majority of questions will be a simple multiple choice. A minority of questions will ask you to write a short sentence or two to answer them.
The first section will ask you about your recent experiences with social situations. It involves 20 multiple choice questions.
The second section will ask you about actions you have taken during recent social situations. It involves 28 multiple choice questions and 5 short written questions.
The third section will ask you about your recent experience with emotional touch. It involves 11 multiple choice questions and 5 short written questions.
Once you complete the third section you are done and will have the opportunity to submit your email for future participation or contact the researcher to ask more questions.

What are the possible disadvantages and risks of taking part?

This survey will take approximately 15 minutes of your time to complete. It will ask you about some potentially stressful or unpleasant experiences you have lived through, which may be distressing for some participants. You are free to complete this survey whenever and wherever you wish and can take more or less than 15 minutes if you wish to help cope with any stress incurred.

What are the possible benefits of taking part?

By completing this survey you will be entered into a prize draw for a £40 Amazon voucher. Once the survey closes, one random respondent will receive this voucher. You will also be given the opportunity to find out more about this study and the research it is helping to inform.

Will my taking part in this study be kept confidential?

All information which collected, or responses provided, during the course of the research will be kept strictly confidential. You will be identified by an ID number which in no way will be able to be connected to you. Please note that assurances on confidentiality will be strictly adhered to unless evidence of serious harm, or risk of serious harm, is uncovered. In such cases the University may be obliged to contact relevant statutory bodies/agencies.

What will happen to the results of the research study?

The results will be held and owned by the researcher and the University of Glasgow. The results can be outlined to the participants whenever they become available. The participants won’t be identified in any report or publication.

Who is organising and funding the research?

This research is funded by the School of Computing Science.

Who has reviewed the study?

The project has been reviewed by the College Ethics Committee.

Contact for Further Information:

You can contact the researcher of this study Shaun Macdonald via the following methods:
Email: s.macdonald.5@research.gla.ac.uk
Thank you for volunteering to take part in this study.

Page 2: Consent Form

Consent Form

Before agreeing to this consent form, you should read the information sheet found on the previous page of the survey, which explains its general purpose.

In this survey, you will be asked about your experiences with social situations and emotional touch. All data is recorded anonymously. The data will be treated as confidential and kept in secure storage at all times. The material may be used in future academic research and publications, both print and online. The survey will take approximately 10 minutes to complete and one participant will be randomly drawn to win a £40 Amazon voucher once the survey closes. If you are a student, no course credits will be awarded for completing this study. You can withdraw from the study at any time. Lastly, to take part in this study, the following criteria must be met:

- I am at least 18 years old.

Experimenter details: Mr Shaun Macdonald (s.macdonald.5@research.gla.ac.uk,)

Supervisor details: Professor Stephen Brewster (stephen.brewster.glasgow.gla.ac.uk, 0141-330-4966)

This study has been approved by the Ethics Committee (Reference Number: 300180278).

Demographic Information

Please indicate your age: ✱ *Required*

Please indicate your gender: ✱ *Required*

- Female
- Male
- Non-Binary
- Other
- Prefer not to say

Please enter your email address: (this will be needed to contact you should you win the £40 voucher prize draw)

If you consent to take part in this survey, click Next to proceed.

If you click 'Next' this will be taken as indication of your consent.

Page 3: Social Interaction Anxiety Scale (SIAS)

For each item, please check a number to indicate the degree to which you feel the statement is characteristic or true for you.

The rating scale is as follows:

0 = Not at all characteristic or true of me.

1 = Slightly characteristic or true of me.

2 = Moderately characteristic or true of me.

3 = Very characteristic or true of me.

4 = Extremely characteristic or true of me.

	0	1	2	3	4
I get nervous if I have to speak with someone in authority (teacher, boss, etc.).	○	○	○	○	○
I have difficulty making eye contact with others.	○	○	○	○	○
I become tense if I have to talk about myself or my feelings.	○	○	○	○	○
I find it difficult to mix comfortably with the people I work with.	○	○	○	○	○
I find it easy to make friends my own age.	○	○	○	○	○
I tense up if I meet an acquaintance in the street.	○	○	○	○	○
When mixing socially, I am uncomfortable.	○	○	○	○	○
I feel tense if I am alone with just one other person.	○	○	○	○	○
I am at ease meeting people at parties, etc.	○	○	○	○	○
I have difficulty talking with other people.	○	○	○	○	○
I find it easy to think of things to talk about.	○	○	○	○	○
I worry about expressing myself in case I appear awkward.	○	○	○	○	○

I find it difficult to disagree with another’s point of view.	○	○	○	○	○
I have difficulty talking to attractive persons of the opposite sex.	○	○	○	○	○
I find myself worrying that I won’t know what to say in social situations.	○	○	○	○	○
I am nervous mixing with people I don’t know well.	○	○	○	○	○
I feel I’ll say something embarrassing when talking.	○	○	○	○	○
When mixing in a group, I find myself worrying I will be ignored.	○	○	○	○	○
I am tense mixing in a group.	○	○	○	○	○
I am unsure whether to greet someone I know only slightly.	○	○	○	○	○

Page 4: Safety Behaviours Part 1

Please indicate which of the following actions you have performed during recent social situations.

The rating scale is as follows:

0 = I have never performed this action.

1 = I have occasionally wanted to perform this action.

2 = I have occasionally performed this action.

3 = I have regularly performed this action.

4 = I have often performed this action.

	0	1	2	3	4
I try to find a space to be alone.	○	○	○	○	○
I avoid making direct eye contact.	○	○	○	○	○
I focus on my phone or some other device.	○	○	○	○	○
I fidget with my clothes, a toy, or some other object.	○	○	○	○	○
I avoid speaking and stay as quiet as possible.	○	○	○	○	○
I start speaking far more than usual.	○	○	○	○	○
I reach out to a pet or other animal.	○	○	○	○	○
I reach out to touch or hug a friend.	○	○	○	○	○
I reach out to touch or hug a family member or loved one.	○	○	○	○	○
I perform some other action (please indicate below).	○	○	○	○	○

If you selected that you perform some other action please indicate it here:

Page 5: Safety Behaviours Part 2

For each item, indicate whether you are more likely to perform this action during public social situations or private social situations.

An example of a public social situation might be a conversation at a restaurant surrounded by lots of strangers or peers.

An example of a private social situation might be a conversation in your home between only you and your conversation partner(s).

The rating scale is as follows:

Neither = I would not perform this action in public or in private.

Public = I am more likely to perform this action in public.

Private = I am more likely to perform this action in private.

Either = I am would perform this action in public and in private.

	Neither	Public	Private	Either
I try to find a space to be alone.	○	○	○	○
I avoid making direct eye contact.	○	○	○	○
I focus on my phone or some other device.	○	○	○	○
I fidget with my clothes, a toy, or some other object.	○	○	○	○
I avoid speaking and stay as quiet as possible.	○	○	○	○
I start speaking far more than usual.	○	○	○	○
I reach out to a pet or other animal.	○	○	○	○
I reach out to touch or hug a friend.	○	○	○	○
I reach out to touch or hug a family member or loved one.	○	○	○	○
I perform some other action (please indicate below).	○	○	○	○

If you selected that you perform some other action please indicate it here:

Page 6: Safety Behaviours Part 3

Please indicate which of the following actions makes you feel calmer when you are feeling stressed or anxious.

The rating scale is as follows:

1= It makes me feel significantly less calm.

2 = It makes me feel a little less calm.

3 = It doesn't change how calm I feel.

4 = It makes me feel a little more calm.

5 = It makes me feel significantly more calm.

	1	2	3	4	5
I try to find a space to be alone.					
I avoid making direct eye contact.					
I focus on my phone or some other device.					
I fidget with my clothes, a toy, or some other object.					
I avoid speaking and stay as quiet as possible.					
I start speaking far more than usual.					
I reach out to a pet or other animal.					
I reach out to touch or hug a friend.					
I reach out to touch or hug a family member or loved one.					
I perform some other action (please indicate below).					

If you selected that you perform some other action please indicate it here:

Page 7: Emotional Touch Part 1

The following two questions concern your experiences with touching and being touched by others. Examples of touch might be hugging, shaking hands and resting one's hand on another's shoulder.

Please indicate which of the following situations involving touch that you find calming.

The rating scale is as follows:

0 = Not at all characteristic or true of me.

1 = Slightly characteristic or true of me.

2 = Moderately characteristic or true of me.

3 = Very characteristic or true of me.

4 = Extremely characteristic or true of me.

	0	1	2	3	4
I find it calming to reach and touch friends.	○	○	○	○	○
I find it calming to reach out and touch my partner/lover.	○	○	○	○	○
I find it calming to reach out and touch a family member.	○	○	○	○	○
I find it calming to reach out and touch a pet or other animal.	○	○	○	○	○
I find it calming to reach out and touch a possession.	○	○	○	○	○

Page 8: Emotional Touch Part 2

The following two questions concern your experiences with touching and being touched by others. Examples of touch might be hugging, shaking hands and resting one's hand on another's shoulder.

Please indicate how comfortable you normally feel in the following situations.

The rating scale is as follows:

0 = Not at all comfortable.

1 = Slightly uncomfortable.

2 = Niether comfortable or uncomfortable.

3 = Somewhat comfortable.

4 = Very comfortable.

	0	1	2	3	4
A friend touches me in a social situation.	○	○	○	○	○
A partner/lover touches me in a social situation.	○	○	○	○	○
A family member touches me in a social situation.	○	○	○	○	○
My or somebody else's pet touches me in a social situation.	○	○	○	○	○

Are you more comfortable sharing social touch in public or in private?

Why?

Page 9: End of Survey

Thank you for taking part in this research!

You will now be entered into a prize draw for a £40 Amazon Voucher, which will be awarded to one lucky participant after the survey closes in September.

If you have any questions about this research or survey, please feel free to email Shaun Macdonald at

B.5 Survey 2

B.5.1 Information Sheet, Consent Form and Survey

An Exploration of User Tactile and Audio Preferences for Relaxation

Page 1: Study Information

Introduction:

You are being invited to take part in a research study. 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.

Purpose of the study:

The purpose of this study is to investigate the individuals' audio and tactile sensory preferences to inform future research. This survey will also contain a social anxiety scale to identify if there are any trends between sensory preferences and shyness or social anxiety.

The results of this study's investigation will be used to shape the design of touch sensations designed to help calm and relax individuals during anxious periods in a future participatory design study.

What requirements do I have to meet to take part?

You must be an adult and have both tactile and sound sensory experience to take part.

Do I have to take part?

The participation in the study is voluntary. You may decide whether or not to take part. If you do decide to take part, you will be asked to fill out an online consent form. If you decide to take part, you are still free to withdraw at any time and without giving a reason.

What will happen to me if I take part?

You will be tasked with answering a survey with 3 main sections. Each question will ask you to write a short answer based on your sensory preferences. Some may also contain a follow-up multiple choice selection.

The first section will ask you to picture yourself into different social scenarios and asks what tactile or audio sensations might be soothing or relaxing in that situation.

The second section will ask you to write what other relaxing activities or sensations you use to relax yourself.

The third section will ask you to complete the Social Interaction Anxiety Scale, a standardised scale for rating shyness and social anxiety.

Once you complete the third section you are done and will have the opportunity to submit your email for future participation or contact the researcher to ask more questions.

What are the possible disadvantages and risks of taking part?

This survey will take approximately 10 minutes of your time to complete. You are free to complete this survey whenever and wherever you wish and can take more or less than 10 minutes if you wish to help cope with any stress incurred.

What are the possible benefits of taking part?

By completing this survey you will be entered into a prize draw for a £40 Amazon voucher. Once the survey closes, one random respondent will receive this voucher. You will also be given the opportunity to find out more about this study and the research it is helping to inform.

Will my taking part in this study be kept confidential?

All information which collected, or responses provided, during the course of the research will be kept strictly confidential. You will be identified by an ID number which in no way will be able to be connected to you. Please note that assurances on confidentiality will be strictly adhered to unless evidence of serious harm, or risk of serious harm, is uncovered. In such cases the University may be obliged to contact relevant statutory bodies/agencies.

What will happen to the results of the research study?

The results will be held and owned by the researcher and the University of Glasgow. The results can be outlined to the participants whenever they become available. The participants won't be identified in any report or publication.

Who is organising and funding the research?

This research is funded by the School of Computing Science.

Who has reviewed the study?

The project has been reviewed by the College Ethics Committee.

Contact for Further Information:

You can contact the researcher of this study Shaun Macdonald via the following methods:

Email: s.macdonald.5@research.gla.ac.uk

Thank you for volunteering to take part in this study.

Page 2: Consent Form

Before agreeing to this consent form, you should read the information sheet found on the previous page of the survey, which explains its general purpose.

In this survey, you will be asked about your preferences for tactile and audio sensations in social situations. All data is recorded anonymously. The data will be treated as confidential and kept in secure storage at all times. The material may be used in future academic research and publications, both print and online. The survey will take approximately **10 minutes** to complete and one participant will be randomly drawn to win a £40 Amazon voucher once the survey closes. If you are a student, **no course credits** will be awarded for completing this study. You can withdraw from the study at any time. Lastly, to take part in this study, the following criteria must be met:

- I am at least 18 years old.
- I have a functioning sense of touch and hearing.

Experimenter details: Mr Shaun Macdonald **(**s.macdonald.5@research.gla.ac.uk,)

Supervisor details: Professor Stephen Brewster (stephen.brewster.glasgow.gla.ac.uk, 0141-330-4966)

This study has been approved by the Ethics Committee (300190137).

Demographic Information

1. Please indicate your age: ✱ *Required*

2. Please indicate your gender: ✱ *Required*

- Female
- Male
- Non-Binary
- Other
- Prefer Not To Say

3. Please enter your email address (this will be needed to contact you should you win the £40 voucher prize draw). This information will be deleted as soon as a random winner is determined and will not be stored with any privately or publicly available data .

If you consent to take part in this survey, click Next to proceed.

If you click 'Next' this will be taken as indication of your consent.

Page 3: Relaxing Sensations 1/4

We are researching new kinds of vibration sensations based on real world sounds or tactile sensations. We theorise that an object held in the hand, which presents vibrations that remind users of previous relaxing or pleasant audio and tactile sensations, could be calming. This survey aims to identify which sounds, tactile sensations and other sensory experiences users might find relaxing or pleasant.

This section will ask you to picture yourself in different social scenarios and imagine what pleasant sound or tactile sensation might make you feel calmer and more relaxed. We will then present you with a selection of sounds and sensations others have previously enjoyed or suggested and you can indicate if you imagine any of those would also be calming.

1

Scenario: You are taking part in a job interview and are being asked unexpected questions to which you don't know the correct answer.

4. If you could choose to feel any touch sensation or hear any sound to relax you in this scenario, what would you choose? ✱ *Required*

5. Are there any sounds or sensations among the selection listed here that you might also find relaxing? Please select as many as you wish, or feel free to add your own suggestions. ✱ *Required*

- [ ] Running Water
- [ ] Vacuum Cleaner
- [ ] Muffled Conversation
- [ ] Scratching

- ☐ Keyboard Clicks
- ☐ Slow Breathing
- ☐ Footsteps
- ☐ Cat Purring
- ☐ Skin Stroking
- ☐ Fidgeting with a Phone or Other
- ☐ Car Engine Idling
- ☐ Brushing
- ☐ Rain
- ☐ Wind
- ☐ Waves Crashing
- ☐ Hairdryer
- ☐ Holding a Warm Mug
- ☐ Feeling a Slow Heartbeat
- ☐ Other

5.a. If you selected Other, please specify:

Page 4: Relaxing Sensations 2/4

Scenario: You are in a bar sitting with a group of people you don't know very well who are talking more to each other than to you.

6. If you could choose to feel any touch sensation or hear any sound to relax you in this scenario, what would you choose? ✱ *Required*

7. Are there any sounds or sensations among the selection listed here that you might also find relaxing? Please select as many as you wish, or feel free to add your own suggestions. ✱ *Required*

- [ ] Running Water
- [ ] Vacuum Cleaner
- [ ] Muffled Conversation
- [ ] Scratching
- [ ] Keyboard Clicks
- [ ] Slow Breathing
- [ ] Footsteps
- [ ] Cat Purring
- [ ] Skin Stroking
- [ ] Fidgeting with a Phone or Other
- [ ] Car Engine Idling
- [ ] Brushing
- [ ] Rain

- Wind
- Waves Crashing
- Hairdryer
- Feeling a Slow Heartbeat
- Other
- Holding a Warm Mug

7.a. If you selected Other, please specify:

Page 5: Relaxing Sensations 3/4

Scenario: You are having a quiet one-to-one conversation with a friend in a cafe over a serious personal matter.

8. If you could choose to feel any touch sensation or hear any sound to relax you in this scenario, what would you choose? ✱ *Required*

9. Are there any sounds or sensations among the selection listed here that you might also find relaxing? Please select as many as you wish, or feel free to add your own suggestions. ✱ *Required*

- ☐ Running Water
- ☐ Vacuum Cleaner
- ☐ Muffled Conversation
- ☐ Scratching
- ☐ Keyboard Clicks
- ☐ Slow Breathing
- ☐ Footsteps
- ☐ Cat Purring
- ☐ Skin Stroking
- ☐ Fidgeting with a Phone or Other
- ☐ Car Engine Idling
- ☐ Brushing
- ☐ Rain
- ☐ Wind

- ☐ Waves Crashing
- ☐ Hairdryer
- ☐ Feeling a Slow Heartbeat
- ☐ Other
- ☐ Holding a Warm Mug

9.a. If you selected Other, please specify:

Page 6: Relaxing Sensations 4/4

Scenario: You are at home having an important discussion with your partner about your relationship.

10. If you could choose to feel any touch sensation or hear any sound to relax you in this scenario, what would you choose? ✱ *Required*

11. Are there any sounds or sensations among the selection listed here that you might also find relaxing? Please select as many as you wish, or feel free to add your own suggestions. ✱ *Required*

- [ ] Running Water
- [ ] Vacuum Cleaner
- [ ] Muffled Conversation
- [ ] Scratching
- [ ] Keyboard Clicks
- [ ] Slow Breathing
- [ ] Footsteps
- [ ] Cat Purring
- [ ] Skin Stroking
- [ ] Fidgeting with a Phone or Other
- [ ] Car Engine Idling
- [ ] Brushing
- [ ] Rain
- [ ] Wind

- [ ] Waves Crashing
- [ ] Hairdryer
- [ ] Feeling a Slow Heartbeat
- [ ] Holding a Warm Mug
- [ ] Other

11.a. If you selected Other, please specify:

Page 7: Other Sensory Preferences 1/3

In this section we will ask you about some other preferences for different sensory experiences. Please write any answers that come to mind for each question and provide context if possible.

1. Texture

12. Please write one or more textures that you find pleasant to touch. ✱ *Required*

13. Please write the contexts in which you prefer these textures. ✱ *Required*

Page 8: Other Sensory Preferences 2/3

2. Form Factor

14. Please write one or more objects that you fidget with when you are stressed. ✱ *Required*

15. Please write the contexts in which you prefer to fidget with certain objects. ✱ *Required*

Page 9: Other Sensory Preferences 3/3

3. Relaxation

16. Please write one or more ways that you relax and unwind to combat a stressful day or experience. ✱ *Required*

17. Please write if the activity you choose depends on situation or context. ✱ *Required*

Page 10: Social Interaction Anxiety Scale (SIAS)

Finally, we would like to ask you to fill in this social anxiety scale. This will allow us to see if there are trends between levels of shyness or social anxiety and the sensory preferences participants had.

For each item, please check a number to indicate the degree to which you feel the statement is characteristic or true for you.

18.

	Not at all	Slightly	Moderately	Very	Extremely
I get nervous if I have to speak with someone in authority (teacher, boss).	○	○	○	○	○
I have difficulty making eye contact with others.	○	○	○	○	○
I become tense if I have to talk about myself or my feelings.	○	○	○	○	○
I find it difficult to mix comfortably with the people I work with.	○	○	○	○	○
I find it easy to make friends my own age.	○	○	○	○	○
I tense up if I meet an acquaintance in the street.	○	○	○	○	○
When mixing socially, I am uncomfortable.	○	○	○	○	○
I feel tense when I am alone with just one person.	○	○	○	○	○
I am at ease meeting people at parties, etc.	○	○	○	○	○

I have difficulty talking with other people.	○	○	○	○	○
I find it easy to think of things to talk about.	○	○	○	○	○
I worry about expressing myself in case I appear awkward.	○	○	○	○	○
I find it difficult to disagree with another’s point of view.	○	○	○	○	○
I have difficulty talking to attractive persons of the opposite sex.	○	○	○	○	○
I find myself worrying that I won’t know what to say in social situations.	○	○	○	○	○
I am nervous mixing with people I don’t know well.	○	○	○	○	○
I feel I’ll say something embarrassing when talking.	○	○	○	○	○
When mixing in a group, I find myself worrying I will be ignored.	○	○	○	○	○
I am tense mixing in a group.	○	○	○	○	○
I am unsure whether to greet someone I know only slightly.	○	○	○	○	○

Page 11: Final page

Thank you for taking part in this research!

You will now be entered into a prize draw for a £40 Amazon Voucher, which will be awarded to one randomly selected participant after the survey closes in May.

If you have any questions about this research or survey, please feel free to email Shaun Macdonald at s.macdonald.5@research.gla.ac.uk.

B.6 Participatory Prototyping

B.6.1 Information Sheet

PARTICIPANT INFORMATION SHEET

Date: 25/11/2020

Title: Participatory Prototyping of Emotionally Resonant Vibrotactile Objects with Socially Anxious and Shy Users

You are being invited to take part in a research study. 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.

Purpose of the study:

The purpose of this study is to prototype some vibrating objects designed to be reminiscent of real world sensations like rain or cat purring, to assess if these objects could prove relaxing and therapeutic for users with social anxiety or shyness.

In a previous study we found results we experimented with vibrotactile sensations that reminded users of sensations they had some prior emotional connection with, such as cat purring or waves crashing. Our results suggested that when users had a prior connection, they could have a similar emotional response to the vibration that they had to the original sensation.

We hypothesise that these sensations could be used as relaxing and comforting stimuli for users with social anxiety in stressful situations.

In this study we want to investigate this concept further alongside participants with shyness or social anxiety, observing what sensations, form factors and textures they choose, as well as how helpful or potentially useful they feel their creations would be to their lived experiences.

Why have you been chosen:

You have been chosen because you are an adult who has been rated as shy or socially anxious on the SIAS (Social Interaction Anxiety Scale), either in a previous survey performed by this researcher or during recruitment for this study.

Do I have to take part?

The participation in the study is voluntary. You may decide whether or not to take part. If you do decide to take part, you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part, you are still free to withdraw at any time and without giving a reason.

What will happen to me if I take part?

If you take part, you will attend a 1-1 session with a researcher for approximately 1 hour. Each session will consist of 4 main sections described below.

In the first section the researcher will introduce the sessions and its purpose, then prompt a short discussion between the participant and researcher on their experiences with shyness or social anxiety. This will include things that trigger anxiety and what coping mechanisms are used. You will be asked to fill out a questionnaire designed to assess social anxiety, the Social Interaction Anxiety Scale, or SIAS. Your score will be kept along with the rest of your data from the session and anonymised.

In the second section the researcher will introduce the main task, individually prototyping an object with a choice of form factor, texture, shape and vibrotactile sensation. The participant will be introduced to the materials they can use to create their individual design. Following this, the participant will have approximately 20-25 minutes to create a personal prototype based on their own preferences. The researcher will be on hand to help with any issues.

In the third section, once the participant has a design, the researcher will ask them to detail their design. Then there will be a small discussion on the design and why it was chosen.

Finally, after this discussion, the participant will fill out a short questionnaire about their experience, then will be given the opportunity to ask any questions or raise any concerns they have with the researcher.

What are the possible disadvantages and risks of taking part?

This session will take approximately 1 hour of your time to complete. It will be a 1-1 session featuring some discussion. Some of the discussion will involve prior experiences of anxiety which could be distressing, as could the social interaction required to take part in the meeting. Due to this during the session you are free to leave at any time, with or without giving a reason.

What are the possible benefits of taking part?

You will be paid one £10 Amazon Voucher for up to one hour of your time and you will have the chance to learn the outcomes of the following study.

Will my taking part in this study be kept confidential?

Your identify will be confidential in any reported results of the study. During the session all discussion will be recorded by a microphone and later drawn up in an anonymised transcript. The original sound recordings will then be deleted and will not be stored in future.

What will happen to the results of the research study?

The results will be held and owned by the researcher and the University of Glasgow. The results can be outlined to the participants whenever they become available.

Who is organising and funding the research?

This research is funded by the School of Computing Science.

Who has reviewed the study?

The project has been reviewed by the College Ethics Committee.

Contact for Further Information:

You can contact the researcher of this study Shaun Macdonald via the following methods:

Email: s.macdonald.5@research.gla.ac.uk

Thank you for volunteering to take part in this study.

Haptic Stimuli Library

1. Small Stream
2. Brushing
3. Car Engine
4. Cat Purring
5. Slow Heartbeat
6. Raindrops
7. Slow Breathing
8. Bubbles
9. Waves Crashing

B.6.2 Consent Form

Participatory Prototyping of Emotionally Resonant Vibrotactile Objects with Socially Anxious and Shy Users

CONSENT FORM

Please tick to confirm your consent:

I confirm that I have read and understood the Participant Information Sheet dated 25/11/2020.

I confirm that I have read and understood the Privacy Notice version 25/11/2020.

I have had the opportunity to think about the information, ask questions and understand the answers I have been given.

I am over 18 years of age.

I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason.

I confirm that I agree to the way my data will be collected and processed and that data will be stored for up to 10 years in University archiving facilities in accordance with relevant Data Protection policies and regulations.

I understand that all data and information I provide will be kept confidential and will be seen only by study researchers and regulators whose job it is to check the work of researchers.

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 understand that if I withdraw from the study, my data collected up to that point will be retained and used for the remainder of the study.

I agree to take part in the study.

Experimenter details: Mr Shaun Macdonald **(**s.macdonald.5@research.gla.ac.uk,)

Supervisor details: Professor Stephen Brewster (stephen.brewster.glasgow.gla.ac.uk, 0141-330-4966)

This study has been approved by the Ethics Committee (Reference Number Pending).

By signing this form, you have read the conditions stated above and agree to take part in the study.

FULL NAME: ____

SIGNATURE: ____

DATE: ____

EMAIL (if you want to be added to the participant's pool):

____

University of Glasgow | School of Computing Science

GIST Glasgow Interactive Systems Group

Participatory Prototyping of Emotionally Resonant Vibrotactile Objects with Socially Anxious and Shy Users

Demographic Information (optional) AGE: ____ GENDER: ____

B.6.3 Questionnaire

POST-SESSION PARTICIPANT SURVEY

Date: 25/11/2020

Title: Participatory Prototyping of Emotionally Resonant Vibrotactile Objects with Socially Anxious and Shy Users

Please respond to each question by circling a number on a scale of 1 to 5, where 1 means you strongly disagree and 5 means you strongly agree.

1. My experience in this participatory design made me feel anxious.
   1 2 3 4 5
2. I found this experience rewarding and satisfying.
   1 2 3 4 5
3. The researcher made me feel comfortable and informed during the session.
   1 2 3 4 5
4. I felt that my input was valued and listened to by the researcher.
   1 2 3 4 5
5. I was able to create a design that was tailored to my personal experiences.
   1 2 3 4 5
6. I found my finished vibrotactile prototype pleasant to hold.
   1 2 3 4 5
7. My vibrotactile prototype successfully captured the sensation I wanted.
   1 2 3 4 5
8. Holding my vibrotactile prototype was a relaxing experience.
   1 2 3 4 5
9. The vibration in my prototype was an important part of the overall experience.
   1 2 3 4 5
10. The shape and texture of my prototype was an important part of the overall experience.
    1 2 3 4 5

11. I wanted the vibration of my prototype to match its texture and shape.
    1 2 3 4 5

12. I could see objects like my prototype being helpful when I am in an anxious situation.
    1 2 3 4 5

13. If you have any further comments or suggestions please write them below.

    ………

    ………

    ………

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    ………

    ………

    ………

Contact for Further Information:

You can contact the researcher of this study Shaun Macdonald via the following methods:

Email: s.macdonald.5@research.gla.ac.uk

Thank you for volunteering to take part in this study.

B.7 Experiment 4

B.7.1 Information Sheet

PARTICIPANT INFORMATION SHEET

Date: 25/11/2020

Title: Participatory Prototyping of Emotionally Resonant Vibrotactile Objects with Socially Anxious and Shy Users

You are being invited to take part in a research study. 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.

Purpose of the study:

The purpose of this study is to prototype some vibrating objects designed to be reminiscent of real world sensations like rain or cat purring, to assess if these objects could prove relaxing and therapeutic for users with social anxiety or shyness.

In a previous study we found results we experimented with vibrotactile sensations that reminded users of sensations they had some prior emotional connection with, such as cat purring or waves crashing. Our results suggested that when users had a prior connection, they could have a similar emotional response to the vibration that they had to the original sensation.

We hypothesise that these sensations could be used as relaxing and comforting stimuli for users with social anxiety in stressful situations.

In this study we want to investigate this concept further alongside participants with shyness or social anxiety, observing what sensations, form factors and textures they choose, as well as how helpful or potentially useful they feel their creations would be to their lived experiences.

Why have you been chosen:

You have been chosen because you are an adult who has been rated as shy or socially anxious on the SIAS (Social Interaction Anxiety Scale), either in a previous survey performed by this researcher or during recruitment for this study.

Do I have to take part?

The participation in the study is voluntary. You may decide whether or not to take part. If you do decide to take part, you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part, you are still free to withdraw at any time and without giving a reason.

What will happen to me if I take part?

If you take part, you will attend a 1-1 session with a researcher for approximately 1 hour. Each session will consist of 4 main sections described below.

In the first section the researcher will introduce the sessions and its purpose, then prompt a short discussion between the participant and researcher on their experiences with shyness or social anxiety. This will include things that trigger anxiety and what coping mechanisms are used. You will be asked to fill out a questionnaire designed to assess social anxiety, the Social Interaction Anxiety Scale, or SIAS. Your score will be kept along with the rest of your data from the session and anonymised.

In the second section the researcher will introduce the main task, individually prototyping an object with a choice of form factor, texture, shape and vibrotactile sensation. The participant will be introduced to the materials they can use to create their individual design. Following this, the participant will have approximately 20-25 minutes to create a personal prototype based on their own preferences. The researcher will be on hand to help with any issues.

In the third section, once the participant has a design, the researcher will ask them to detail their design. Then there will be a small discussion on the design and why it was chosen.

Finally, after this discussion, the participant will fill out a short questionnaire about their experience, then will be given the opportunity to ask any questions or raise any concerns they have with the researcher.

What are the possible disadvantages and risks of taking part?

This session will take approximately 1 hour of your time to complete. It will be a 1-1 session featuring some discussion. Some of the discussion will involve prior experiences of anxiety which could be distressing, as could the social interaction required to take part in the meeting. Due to this during the session you are free to leave at any time, with or without giving a reason.

What are the possible benefits of taking part?

You will be paid one £10 Amazon Voucher for up to one hour of your time and you will have the chance to learn the outcomes of the following study.

Will my taking part in this study be kept confidential?

Your identify will be confidential in any reported results of the study. During the session all discussion will be recorded by a microphone and later drawn up in an anonymised transcript. The original sound recordings will then be deleted and will not be stored in future.

What will happen to the results of the research study?

The results will be held and owned by the researcher and the University of Glasgow. The results can be outlined to the participants whenever they become available.

Who is organising and funding the research?

This research is funded by the School of Computing Science.

Who has reviewed the study?

The project has been reviewed by the College Ethics Committee.

Contact for Further Information:

You can contact the researcher of this study Shaun Macdonald via the following methods:

Email: s.macdonald.5@research.gla.ac.uk

Thank you for volunteering to take part in this study.

Haptic Stimuli Library

1. Small Stream
2. Brushing
3. Car Engine
4. Cat Purring
5. Slow Heartbeat
6. Raindrops
7. Slow Breathing
8. Bubbles
9. Waves Crashing

B.7.2 Consent Form

Participatory Prototyping of Emotionally Resonant Vibrotactile Objects with Socially Anxious and Shy Users

CONSENT FORM

Please tick to confirm your consent:

I confirm that I have read and understood the Participant Information Sheet dated 25/11/2020.

I confirm that I have read and understood the Privacy Notice version 25/11/2020.

I have had the opportunity to think about the information, ask questions and understand the answers I have been given.

I am over 18 years of age.

I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason.

I confirm that I agree to the way my data will be collected and processed and that data will be stored for up to 10 years in University archiving facilities in accordance with relevant Data Protection policies and regulations.

I understand that all data and information I provide will be kept confidential and will be seen only by study researchers and regulators whose job it is to check the work of researchers.

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 understand that if I withdraw from the study, my data collected up to that point will be retained and used for the remainder of the study.

I agree to take part in the study.

Experimenter details: Mr Shaun Macdonald **(**s.macdonald.5@research.gla.ac.uk,)

Supervisor details: Professor Stephen Brewster (stephen.brewster.glasgow.gla.ac.uk, 0141-330-4966)

This study has been approved by the Ethics Committee (Reference Number Pending).

By signing this form, you have read the conditions stated above and agree to take part in the study.

FULL NAME: ____

SIGNATURE: ____

DATE: ____

EMAIL (if you want to be added to the participant's pool):

____

University of Glasgow | School of Computing Science   GIST GLASGOW INTERACTIVE SYSTEMS GROUP

Participatory Prototyping of Emotionally Resonant Vibrotactile Objects with Socially Anxious and Shy Users

Demographic Information (optional) AGE: ____ GENDER: ____

B.7.3 Questionnaire

POST-SESSION PARTICIPANT SURVEY

Date: 25/11/2020

Title: Participatory Prototyping of Emotionally Resonant Vibrotactile Objects with Socially Anxious and Shy Users

Please respond to each question by circling a number on a scale of 1 to 5, where 1 means you strongly disagree and 5 means you strongly agree.

1. My experience in this participatory design made me feel anxious.
   1 2 3 4 5

2. I found this experience rewarding and satisfying.
   1 2 3 4 5

3. The researcher made me feel comfortable and informed during the session.
   1 2 3 4 5

4. I felt that my input was valued and listened to by the researcher.
   1 2 3 4 5

5. I was able to create a design that was tailored to my personal experiences.
   1 2 3 4 5

6. I found my finished vibrotactile prototype pleasant to hold.
   1 2 3 4 5

7. My vibrotactile prototype successfully captured the sensation I wanted.
   1 2 3 4 5

8. Holding my vibrotactile prototype was a relaxing experience.
   1 2 3 4 5

9. The vibration in my prototype was an important part of the overall experience.
   1 2 3 4 5

10. The shape and texture of my prototype was an important part of the overall experience.
    1 2 3 4 5

11. I wanted the vibration of my prototype to match its texture and shape.
    1 2 3 4 5

12. I could see objects like my prototype being helpful when I am in an anxious situation.
    1 2 3 4 5

13. If you have any further comments or suggestions please write them below.

    ……………………………………………………………………………………………………

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Contact for Further Information:

You can contact the researcher of this study Shaun Macdonald via the following methods:

Email: s.macdonald.5@research.gla.ac.uk

Thank you for volunteering to take part in this study.

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