Investigation of Thermal Feedback for In-Car Applications

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Abstract

Driving is a highly demanding task and modern cars employ a multitude of sensors and features to aid the driver. Safety can be increased by minimising visual distraction during driving and tactile feedback is often introduced as an alternative to, or an enhancement of, visual icons. Research on tactile in-car feedback is highly focused on vibrotactile feedback, restricting the design space by ignoring other tactile modalities with the potential to increase driving safety. Thermal feedback has been tested for mobile environments and shown high recognition accuracy, with the added advantage of causing potentially strong emotional associations with concepts, such as danger or urgency and familiarity. This thesis, therefore, explores the effectiveness of thermal feedback for in-car applications. The novelty of the feedback within this environment dictates the need to not only investigate the perceptability of this modality as a secondary task during driving, but also the impact of thermal feedback on driving behaviour and workload in a safe environment. Seven driving simulator studies tested different applications and aspects of thermal cues, such as directional cues, binary and in combination with spatial information, and different types of notifications. Results show the challenges and advantages of thermal cue design for presentation during driving and the effectiveness of the modality for navigation. Binary directional cues have high recognition rates, but face the challenge of the return to a neutral base temperature being misinterpreted as new cues. The number of these false positives was especially high for long thermal cues, which had the highest recognition rates. Design choices will have to be made in consideration of this fact. Spatial directional cues were effective, but the simultaneous presentation of cues with opposing direction of temperature change on each hand confused rather than aided the driver. In addition, the perceived urgency of thermal cues was compared to vibration and the two modalities were investigated together for informational notifications. Thermal cues were consistently rated as less urgent than both bimodal and vibrotactile cues. The addition of thermal feedback to urgent vibration cues led to longer reaction times, which renders bimodal tactile stimuli unsuited for urgent warnings. However, they could very accurately convey information to classify messages. Both thermal only and bimodal tactile stimuli had high recognition rates. While thermal feedback could not replace visual information during the transfer of control in a semi-autonomous car, the addition of bimodal tactile feedback led to an improvement of driving behaviour and was preferred by participants. These findings show the potential for thermal feedback within the driving environment.

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Declaration and Contributing Papers

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

Experiments 1 and 2 in Chapter 3 have been published at AutomotiveUI 2018 and a Special Issue of the International Journal of Mobile Human Computer Interaction:

> Di Campli San Vito P., Pollick F., White S., Skrypchuk L., Mouzakitis A., Brewster S.: **Investigation of Thermal Stimuli for Lane Changes**. In *Proceedings of the 10th International ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications - AutoUI '18*, ACM Press, 2018.
> https://doi.org/10.1145/3239060.3239062

> Di Campli San Vito P., Pollick F., White S., Skrypchuk L., Mouzakitis A., Brewster S.: **Thermal Feedback for Simulated Lane Change Scenarios**. In *Special Issue of the International Journal of Mobile Human Computer Interaction (IJMHCI): Recent Advances in Automotive User Interfaces and Interactive Vehicular Applications Research* 11(2), IGI Global, pp. 39-57, 2019.
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A Demonstration of Experiment 3 in Chapter 4 has been presented and published at ICMI 2017:

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> https://doi.org/10.1145/3136755.3143029

Experiments 3 and 4 in Chapter 4 have been demonstrated, presented and published at CHI 2019:

> Di Campli San Vito P., Pollick F., Brown E., Skypchuk L., Mouzakitis A., Brewster S.: **Haptic Navigation Cues on the Steering Wheel**. In *Proceedings of the 37th Annual ACM Conference on Human Factors in Computing Systems – CHI '19*, ACM Press, 2019.
> https://doi.org/10.1145/3290605.3300440

Experiment 5 and 6 in Chapter 5 have been accepted for publication and will be presented at ICMI 2020:

> Di Campli San Vito P., Pollick F., Thompson S., Skypchuk L., Mouzakitis A., Brewster S.: **Purring Wheel: Thermal and Vibrotactile Notifications on the Steering Wheel**. In *Proceedings of the 19th ACM International Conference on Multimodal Interaction – ICMI '20*, ACM Press, 2020.
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Experiment 7 in Chapter 5 has been published and presented as Work in Progress at AutomotiveUI 2020:

> Di Campli San Vito P., Brown E., Pollick F., Thompson S., Skypchuk L., Mouzakitis A., Brewster S.: **Haptic Feedback for the Transfer of Control in Autonomous Vehicles**. In *Adjunct Proceedings of the 12th International ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications - AutoUI '20*, ACM Press, 2020.
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Chapter 1

Introduction

1.1 Motivation

Modern cars utilise a plethora of sensors to improve driving safety and driving experience. Some of these sensors provide information on the state of the world and the car either presents this information to the driver, for example by turning on an icon on the dashboard when the temperature outside sinks under 4°C, or takes immediate action by for example turning on the windscreen wipers when it rains or the lights when it gets dark. Others collect and report data about the state of the car, such as air pressure of the tyres or fuel and oil levels. More recently, car manufacturers have started to embed sensors to observe driving related information, mostly to improve driving safety or efficiency, as for example through lane departure warnings and gear changing instructions. In addition, passengers and drivers alike regularly use the car's integrated entertainment system and even connect personal devices with it, resulting in more communication between the car and its occupants.

The state of the car is typically conveyed through predominantly visual notifications: icons on the dashboard, on the screen in the centre console or on head up displays. However, driving is a highly visual task and the eyes should be fixed on the road ahead, with eyes-off-the-road time considered to be one of the main contributors to crashes and incidents on the road and especially long glances over 2s being safety critical [2]. For many occasions, auditory feedback, as abstract alerts or language-based, are used to lessen the visual and mental workload by providing information in a modality different to that used for the primary task, as suggested in the Multiple Resources Theory [3]. Examples for abstract auditory feedback are pings when the seat-belt is not fastened or when warning icons appear for the first time. Language-based feedback might be navigation instructions. However, audio feedback is not desirable or applicable in all situations: audio feedback can be disruptive when drivers are engaged in conversation or listen to radio programmes, and deaf drivers cannot benefit from this feedback at all. These issues can be overcome by using feedback engaging the sense of touch: haptic feedback. The most common haptic modality used in cars is vibrotactile feedback. Some car manufacturers, such as Honda[1], have integrated vibration on the steering wheel to warn drivers about an imminent lane departure. Research has shown that this feedback can be interpreted without any prior training [4] and can reduce the number of road crashes [5].

Other kinds of in-car applications have also been explored utilising vibrotactile feedback. Navigational cues, for example, have been given through vibration on the seat [6, 7], seat belt [8, 9] or steering wheel [10, 11, 12]. Different haptic modalities such as shear or skin stretching feedback [13, 14] have also been shown to be effective in providing directional information. In addition to lane departure warnings [4, 15, 16], haptic feedback was also investigated for collision warnings [17, 18, 19] and for providing information after a transfer of control back to the driver for autonomously driving cars [20, 21, 22]. In those cases, information is mostly given in a multimodal setting, adding vibrotactile feedback to audio and/or visual cues, as they are usually highly urgent and drivers have to react to them quickly and accurately. Multimodal feedback, especially in combination with vibration, can decrease reaction times [23, 24, 25] and increase the feeling of urgency [26].

This research shows that vibration as a feedback type has many advantages in the driving environment, but there are caveats. Most of the research has been conducted in labs, simulating the car's environment. The influence of real life driving on differing road conditions has not been thoroughly investigated. Naturalistic road situations can include speed bumps, potholes and raised profile edge lines on motorways, which can influence the vibration of the car substantially. In addition, the choice of car and its behaviour to those differing road conditions could have further significant influence on the perceptability of vibrotactile cues during driving. Multimodal feedback could help overcome these issues. Therefore, the investigation of other tactile feedback that could enhance or even replace vibrotactile feedback in a car is advisable.

One such tactile feedback, which has been shown to be effective in bumpy and noisy environments [27], but not yet been investigated for in-car use, is thermal feedback. There has been a rise in research of temperature changes as feedback in human computer interaction over the last few decades. While research has been, and is continually, scoping properties of thermal displays and defining guidelines [28, 29, 30], thermal feedback has found its most popular use case in virtual reality settings. The thermal sense plays an important role in the human's ability to differentiate textures [31, 32] and has been engaged to enhance the feeling of touching and exploring objects in virtual reality [33, 34]. Additionally, temperature has been used to increase immersion into the virtual world by assigning appropriate thermal properties to surroundings [35, 36, 37] and objects [38, 39].

[1]https://www.silkohonda.com/manufacturer-information/honda-sensing/ (accessed 13/12/2019)

Outside of virtual reality, thermal feedback was tested for mobile [40, 29, 41] and stationary [42, 43, 27] use. The investigations ranged from exploring perceptability and influences of different aspects of the thermal stimuli in specific environments, over affective associations with temperatures and use cases for those, to using thermal icons to convey specific (or abstract) information, as well as combinations of those.

Thermal icons have shown high recognition rates for mobile interaction, especially for direction of temperature change (warm/cool), but also for subjective intensity, combining the extent and rate of temperature change [44, 45]. In addition, emotional, or affective, associations with temperatures have been found [46, 47, 48]. While some findings seem contradictory [49], showing that the mapping of temperatures to emotions can be complex and dependent on the context, the shared associations between individuals can be quite strong.

The effect of ambient temperature and clothing on temperature perception has been studied as well [50, 51]. In the well-defined interior of a vehicle, environmental influences can be easily captured and the thermal stimuli potentially adapted. During manual driving, the cues could be presented on the hands, unobstructed by any material. Even in the case of material obstructing direct touch (by wearing gloves, for example), sensors could be embedded into the steering wheel to determine what kind of material is in direct contact with the wheel. Steering wheels already have warming abilities in many modern cars, providing comfort to drivers and passengers alike and adding some familiarity to the concept. The concept of cooling steering wheels, however, is novel.

Before thermal feedback can be used during driving, its safety and effectiveness in this new environment have to be tested. Previous research investigated thermal perception as a main task, with participants' main focus being on the thermal cues. But driving is a highly demanding primary task, which pushes the perception of other cues into the domain of a secondary task. How well will thermal cues be recognised under those conditions? Additionally, distractions from the driving task can have grave and dangerous consequences. Before introducing new stimuli types to this environment, it has to be ensured that they do not negatively influence the driving behaviour. The influence of new modalities, therefore, needs to be tested in a safe environment.

Thermal feedback has the potential to increase driving safety, by minimising the visual load through tactile presentation of information. Haptic feedback in the car is already used to decrease the pressure of visual feedback, but the design space is limited. Thermal feedback can present binary information, such as direction of temperature change, or could be presented on different locations and add spatial information. It could also be combined with vibration and used as bimodal tactile feedback. Temperature has a strong connection to emotion and could enrich in-car feedback with a modality that can be used to design easily understandable notifications with affective associations. The influence of thermal feedback on driver and driving behaviour is, however, unknown and there is a pressing need to understand how best to utilise this modality in the car and understand possible consequences during driving. This thesis, therefore, investigates the effectiveness of thermal feedback for use in vehicular environments.

1.2 Thesis Statement

Haptic feedback within cars is used to reduce visual distraction during driving, one of the main contributors to crashes. This research explores aspects and applications of thermal feedback for in-car use to convey information to the driver non-visually. Results show that thermal cues can be used to convey information to the driver accurately and non-urgently and its effectiveness can be enhanced through multimodal combination with vibrotactile feedback and offers a rich, new modality to broaden the design space of tactile in-car feedback.

1.3 Research Questions

This thesis aims to answer following research questions:

1. **Research Question 1:**
   How accurately can thermal feedback give binary direction cues in an automotive setting (with one thermal device)?

2. **Research Question 2:**
   How accurately can thermal feedback give direction cues in an automotive setting with the spatial information from multiple thermal devices?

3. **Research Question 3:**
   How effectively can thermal feedback convey notifications in a car in a
   a. unimodal setting?
   b. bimodal tactile setting?

1.4 Thesis Outline

Chapter 2, *Literature Review*, reviews literature on thermal perception and thermal cues in human computer interaction. Furthermore, basic concepts needed to investigate interaction in the driving context are discussed, as well as research on the use of haptic feedback within the driving environment. The following chapters discuss the experimental work, an experiment overview is provided in Table 1.1.

In Chapter 3, *Thermal Binary Directional Cues*, Research Question 1 is investigated with two experiments. Both studies presented thermal directional cues on one device, where the direction of temperature change prompted the direction of a lane change. The first experiment, Experiment 1, compared thermal to audio feedback. Experiment 2 explored several factors of the thermal feedback design.

Chapter 4, *Thermal Directional Cues with Multiple Devices on the Steering Wheel*, expands on ideas from the previous chapter and presents navigation information on multiple thermal devices. Experiment 3 compares thermal to audio navigation, Experiment 4 to cutaneous push feedback. These two studies aimed to answer Research Question 2.

Chapter 5, *Unimodal and Multimodal Notifications with Thermal Feedback*, presents three experiments looking into thermal and bimodal tactile notifications. Experiments 5 and 6 answered both parts of Research Question 3 (a. and b.), while Experiment 7 only investigated bimodal aspects (3 b.). While in Experiment 5, the same information (urgency) was presented in the different modalities, Experiment 6 looked at different types of information (Nature and Importance). Experiment 7 explored the benefits of bimodal tactile feedback in a multimodal setting for transfer of control in semi-autonomous cars.

Chapter 6, *Conclusions*, will end the thesis with a summary and discussion of all findings. Additionally, limitations and ideas for future work are proposed. Finally, conclusions and recommendations are presented.

Experiment	Chapter	Research Question	*Modalities* / Goals
Experiment 1	3	1	*thermal vs. audio* Compare recognition, driving behaviour, time and subjective data between thermal and audio cues
Experiment 2	3	1	*thermal* Explore influence of several factors of stimuli design on recognition, false positives and time
Experiment 3	4	2	*thermal vs. audio* Compare effectiveness, subjective and driving data of thermal and audio cues for turn-by-turn navigation
Experiment 4	4	2	*thermal vs. cutaneous push* Compare effectiveness, subjective and driving data of thermal and cutaneous push cues for turn-by-turn navigation Compare subjective data with Experiment 3
Experiment 5	5	3 a./b.	*thermal and/or vibrotactile* Compare thermal, vibrotactile and bimodal stimuli and their influence on perception of notification urgency and recognition rate and time
Experiment 6	5	3 a./b.	*thermal vs. thermal and vibrotactile* Compare recognition and preferences of thermal and bimodal stimuli for notifications with two types of information
Experiment 7	5	3 b.	*thermal and vibrotactile, accompanied by audio and visual* Compare effect of bimodal feedback on gaze, trust and preferences for control transfer of autonomous cars

Table 1.1: Experiment Overview: Describing the modalities (in italic), goals and research questions posed for each experiment presented in this thesis.

Chapter 2

Literature Review

This chapter will describe research needed as basis to answer the questions posed in the previous chapter. In order to use thermal cues in interaction with humans, temperature perception and characteristics of the human skin have to be understood. Section 2.1 will, therefore, provide insights into basic human thermal sensing, followed by an overview of thermal feedback use in human computer interaction in Section 2.2. The second half of the chapter will look into driving related issues. Section 2.3 with provide basics on driving related research and Section 2.4 will concentrate on haptic feedback within the driving environment, to inspire how and for what thermal feedback might be most suitable and effectively used.

2.1 Thermal Perception in Humans

The human body depends on homeostasis, meaning that the core temperature of the body needs to be kept at a relatively stable temperature of around 37°C. Variations in skin temperature, however, occur by simply touching an object [31] and can vary up to 12°C [32]. Thermal comfort describes how satisfied an individual is within their thermal environment. Research has shown that gender can have a significant influence on the hedonistic experience of surrounding temperatures [52, 53] and on the sensitivity of warm temperatures [54], but when temperature was used for interaction, gender effects were found to be negligible [55]. The feeling of temperature comfort is influenced by the core temperature of a person, however, the perception of temperature changes was found to be independent of it [56, 57]. In human computer interaction, thermal feedback is presented peripherally on the skin. The following literature discussion, therefore, will focus on cutaneous thermal perception, temperature perception of the skin. First, basic human thermal sensing is described, followed by specific aspects of thermal perception.

2.1.1 Thermal Receptors and Physiological Effects

The human skin perceives temperature through two types of thermal receptors on free nerve endings: C-fibres, with unmyelinated axons, react to warm temperature changes, while myelinated axons of Aδ-fibres react to cold temperatures [58, 59]. The density of thermal receptors in the skin varies on body location and type of receptor. Small locations of the body that can detect warm or cold temperatures changes are called warm or cold spots, respectively, and encompass only a few millimetres. These are dispersed over the body independent of each other and in differing numbers. More cold than warm spots have been identified [60], with, for example, seven cold spots per 100m^2 on the forearm, but only 0.24 warm spots [32]. In addition to the higher number of cold spots in the skin, cold receptors react faster to temperature changes, with a conduction velocity of 12-30m/s, while warm receptors show a velocity of 0.5-2m/s [59]. In comparison, vibration, detected by Pacinian corpuscles embedded in the subcutaneous layers of the skin, has a conduction velocity of 30-70m/s and can be detected more rapidly [59]. These two factors lead to a difference of thermal sensing of both the direction of temperature change (warm/cold) and on different locations. Over the body, the sensitivity to temperature varies greatly, up to 100-fold, and declines with age [1, 61]. So is, for example, the face very sensitive to thermal changes, while the extremities show poor sensitivity, see Figure 2.1. Cold could be detected better over the whole body than warm, with thermal sensitive spots being better at recognising both directions of change when compared to other regions. The less sensitive regions also decline faster during ageing than the more sensitive regions [1].
Observations of thermal sensitivity on the hands showed temperature changes were easiest to detect on the thenar eminence [62], the glabrous (hairless) skin under the thumb, see Figure 2.2. Temperature changes (from a base temperature of 33°C) of 0.11°C for warm and 0.07°C for cold changes could be detected on the thenar region, while only changes of 0.16°C for warm and 0.12°C for cold could be felt on the less sensitive fingertips [63, 1].

Thermal receptors react to temperature changes on a range of 5°C and 43°C, but cold receptors are most active at around 25°C, while warm receptors peak at 45°C [32]. Additional receptors charge at noxious (harmful) temperatures: if there is a risk of tissue damage, so-called thermal nociceptors convey the feeling of pain. The skin rests at around 32°C to 34°C within a neutral zone of 30°C to 36°C, in which slow temperature changes are hardly detected, as the skin adapts to these [62, 32, 58]. Nociceptors charge when temperature decreases below 12°C or increases above 45°C [58]. Ambient temperature was found to have an influence on the perception of temperature changes: in cold rooms stimulus intensity was rated lower than in neutral environment for both warm and cold temperature changes, but there was no change found between neutral and warm environments [50].

Thermal receptors are underpinned by transient receptor potential (TRP) channels, which

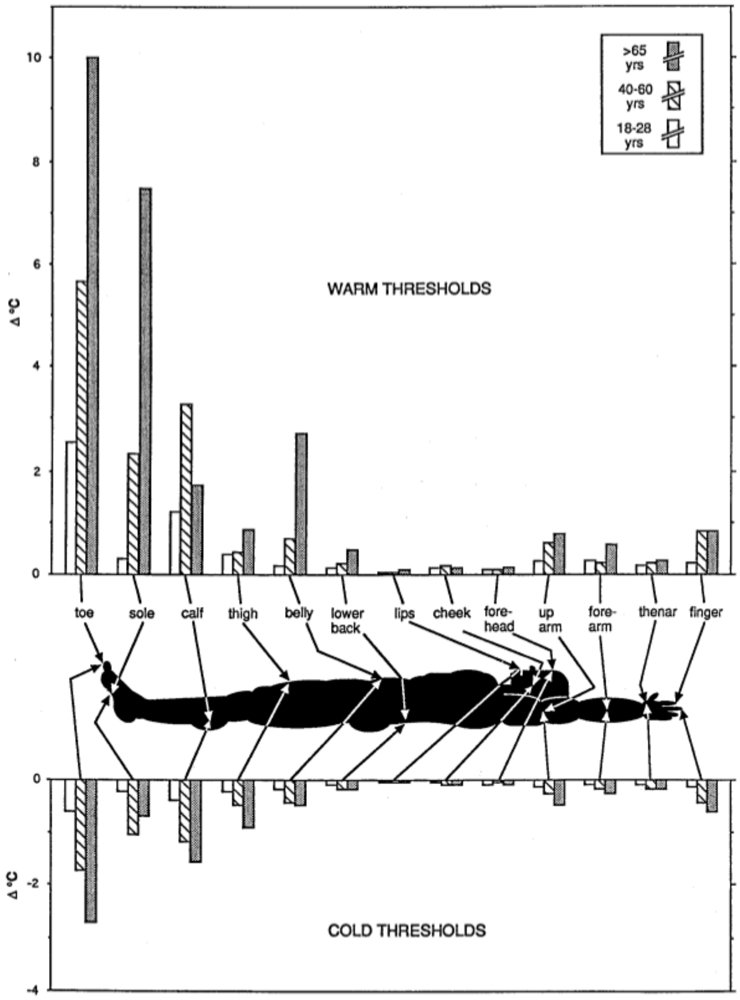


Figure 2.1: Thermal sensitivity over the body: warm (upper section) and cold (bottom section); smaller bars indicate higher sensibility (extracted from [1]).

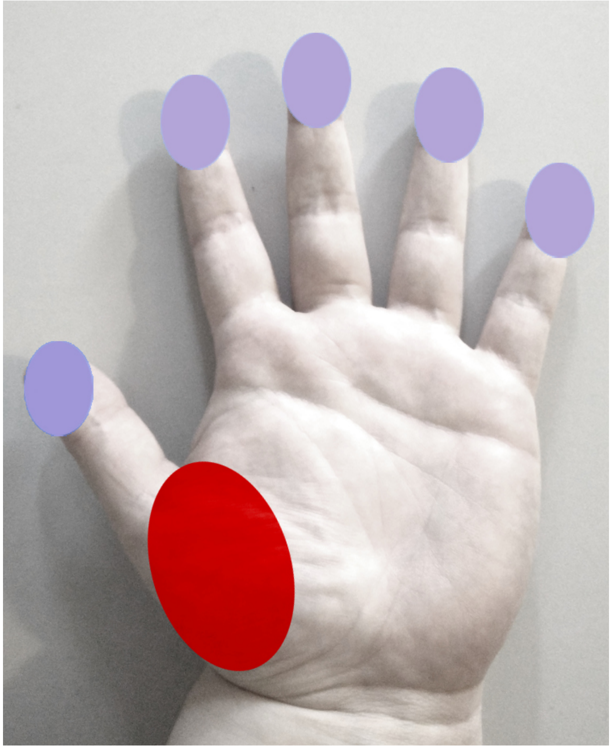


Figure 2.2: Thenar eminence (red) of the hand, the most temperature sensitive part of the inner hand; finger tips (light blue) are less sensitive.

react to different, sometimes overlapping temperature ranges, but can also be activated by *hot* or *cool* food products, such as chilli peppers or mint [32, 58]. Thermal fibres and TRP channels do not operate completely independently [62, 64], influencing each other invoking interactions that could explain some phenomena observed in thermal perception (see Section 2.1.3).

The thermal sense is aiding the identification and discrimination of different types of objects [31, 65, 32]. Thermal properties of materials are especially important, when visual identification is inhibited. The skin temperature changes when touching an object depend on, for example, the object's conductivity and heat capacity, the temperature difference between skin and object and thermal contact resistance between the two [32]. The thermal properties of the object materials have to be sufficiently different for the thermal sense to contribute significantly to object identification [31].

To Summarise: warm and cold temperature sensitivity differs over the surface of the body and perception changes with age. In addition, cold temperatures are perceived faster and over a larger range. The neutral temperature zone of the skin is between 30°C and 36°C and within this range the skin adapts to small temperature changes fast. Temperatures under 12°C and over 45°C lead to painful sensation and potentially tissue damage.

2.1.2 Spatial and Temporal Aspects of Thermal Perception

Thermal perception is dependent on spatial and temporal aspects of the temperature change. Thermal sensation on the skin depends on the size of the area at which a thermal change is presented: the temperature change is perceived as being stronger when it is presented on a larger area of the skin [66, 67, 68]. This is called *spatial summation* and can be observed for both warm [69, 66] and cold changes [67]. For example, when presenting thermal stimuli on the fingertips, it has been found that presenting them on different fingers improved the identification [70, 71]. Even thermal changes on bilateral body parts, such as both hands, are summed up, suggesting that the summation effect itself manifests in the nervous system rather than the skin [68]. The influence of spatial summation on the perception of a thermal stimulus is almost equal to the extent of temperature change itself, i.e. how much the temperature is changed [69, 67]. This means that the same sensation can be simulated by doubling the area and halving the extent of temperature change. For warm temperature changes, this effect of spatial summation decreases when the temperature approaches the pain threshold, but not for cold changes [67]. Spatial summation can, however, inhibit the distinction of two differing thermal stimuli in close proximity [72, 73].

Temporal aspects also play an important role in thermal perception. Human skin adapts to the temperature it is exposed to over time. This temporal adaptation is fast for temperatures close to skin temperature, adapting a temperature difference of 1°C within one minute [32]. For higher temperature differences between 28°C and 37.5°C, complete adaptation can be reached within 25min [74].
Another important temporal factor influences the perceived intensity of the thermal change: how fast the temperature changes. The higher the rate of change (ROC), the faster the skin reacts to the temperature change [75, 76]. For example, a change in ROC from 0.5°C/s to 4°C/s doubled the perceived intensity of the stimulus [77]. In addition, nociceptive (painful) sensations increased for faster temperature changes, more noticeably for warm than cold [75, 77].

2.1.3 Thermal Phenomena

Based on the physiological features of thermal sensing, some interesting interactions of warm and cold cues can be observed. Green [78] observed a couple of thermal phenomena in experiments with three thermal devices, presenting stimuli to three fingers of the same hand. *Referral* described the phenomenon occurring when the outer two fingers were warmed (or cooled), but the middle finger kept thermally neutral: participants reported a warm (or cold) sensation on the middle finger. Prolonged presentation of these stimuli led to adaptation and the temperature differences could be distinguished [79]. *Enhancement* described the

observation of the middle finger feeling warmer (or colder) than the outer two fingers, when the same temperature was presented on all three, while *Domination* described the effect that if the direction of change of the middle finger differed from the outer finger, the same sensation was reported for the middle finger than the outer fingers. The most surprising effect observed was coined *Synthetic Heat*, or *Thermal Grill Illusion*, and occurred sometimes, but not always, when the outer fingers were both warmed and the middle finger was cooled. Not only was the sensation on the middle finger warm, as it would because of Domination, but it was described as *very warm* or *hot*, to the point of mild hot burning sensation [80]. Perceived intensity of this effect was higher for more pronounced temperatures differences [81] and diminished after 10s [80].
These phenomena closely relate to the effect of spatial summation (as described in 2.1.2) and the underlying shared TRP channels (discussed in 2.1.1).

Singhal and Jones [82, 83] investigated if the *cutaneous rabbit* illusion, or *sensory saltation* [84], could also be observed for thermal feedback. When several mechanical stimuli spaced evenly on the skin were being activated in progression, participants reported feeling one smooth movement *as if a tiny rabbit was hopping*. The time intervals between the activation of the stimulators influenced the perception of the location it was presented on. The same effect was found for thermal feedback: for short intervals participants perceived the position of the second pulse to be closer to the location of the third pulse [82, 83].

2.1.4 Summary

Human skin does not perceive temperature equally on all locations. Some areas are more sensitive, such as the face, while others, such as the extremities, have poor sensitivity. On the hands, the thenar region, the palm directly under the thumb, is most sensitive to temperature changes, but thermal changes are still perceivable on the fingers. In addition, the skin more easily perceives cold temperatures and reacts faster to them. The non-painful range of temperature lies within 12°C and 45°C, with the skin's neutral state between 30°C and 36°C, in which it adapts to temperatures fast.
Temperature on the skin feels warmer (or colder), when the area of stimulation is bigger. This spatial summation not only occurs when the areas are adjacent to each other, but can still be observed over several fingers and even bilateral body parts, such as both hands. The speed or rate at which temperature changes occur has a profound influence on the perceived intensity of the change. Faster rates lead to an increased feeling of intensity.
These characteristics of the human thermal sensing constrain and define the possible parameters of thermal displays and cue design. In addition to these, the occurrence of thermal phenomena, especially when presenting warm and cold stimuli in adjacent areas, have to be kept in mind when designing cues, but can be purposefully used to enhance sensations. This

basic knowledge on thermal sensing in humans informed any design of thermal displays used within this thesis. The next section will explore research on thermal feedback within human computer interaction, and discuss design and use of thermal cues.

2.2 Thermal Changes as Feedback

Thermal displays have become more popular in human computer interaction over the last two decades and have been applied to many different kinds of use cases. More abstract observations have brought insights into the design space and limits of thermal displays, discussed in Section 2.2.1, while applied settings have added to the specific requirements needed in defined areas, like Affective Computing (Section 2.2.2), and environments, such as Virtual Reality (Section 2.2.3), and Stationary and Mobile Applications (Section 2.2.4). The bimodal combination of thermal and vibrotactile feedback and their interaction will be discussed separately in Section 2.2.5. Finally, temperature in the driving context will be briefly discussed. This section concentrates on feedback presented on the hands, but discusses feedback on other locations to some degree. Kappers & Plaisier [85] have conducted an extended review of thermal feedback presented on body parts other than hand and face.

2.2.1 Thermal Displays: Characteristics and Design Recommendations

Thermal Display Requirements

Based on human thermal perception, Jones & Berris [28] have proposed properties that should be provided by a thermal display. They identified that devices should be able to present temperatures between 22°C and 42°C. They observed that skin temperatures in a room of approximately 20-22°C stayed between 32°C and 35°C for most subjects, leading to the conclusion that thermal displays do not require constant measuring of skin temperature. The rate of change used in displays should be at least 0.3°C/s to ensure detection. As perceived intensity of a temperature change depends on several factors, such as rate of change, area of presentation and extent of temperature change, the use of discrete temperatures as cue was found to be ineffective.

In addition, thermal perception is sluggish compared to other tactile modalities, such as vibration. But recognition time can be decreased by presenting warm and cold simultaneously on two small, adjacent devices before presenting the stimulus, benefiting from the poor thermal resolution of the skin and the fast adaption to temperature changes close to skin temperature. This method increased the difference of skin temperature and stimulus and led to faster recognition [86, 87].

Thermal Feedback Design

The design of thermal cues was evaluated by Wilson *et al.* [29]. They tested different extents (1°C, 3°C and 6°C) and rates of change (1°C/s and 3°C/s) in both directions on different body locations, starting from a neutral temperature of 32°C, which was presented before and between stimuli. They tested these factors stationary at a table and while walking indoors and summarised their findings as recommendations. They found that stimuli were harder to detect while walking and detection took longer. The thenar eminence and the palm were found to be most sensitive, reaffirming previous findings discussed in Section 2.1.1. In terms of perceptability and comfort, they found that both 1°C/s and 3°C/s were detected with similar accuracy, however, the faster rate of change was detected faster, but rated as less comfortable. Cold temperatures were easier and faster detected than warm cues. The lowest extent of temperature change had the lowest recognition rate, the other two could be identified and even differentiated efficiently.

In further experiments, Wilson *et al.* [44] also investigated thermal icons for the mobile environment. Thermal icons were structured thermal feedback, presenting two types of information: *source* (personal/work) and *importance* (standard/important). Two factors were tested: direction of temperature (source) and subjective intensity (importance), a combination of extent and rate of temperature change. Full icons were identified with 83% accuracy, the single factors direction of change and subjective intensity with 97% and 85% accuracy, respectively.

Singhal & Jones [45] investigated different patterns of thermal cues and how well they could be perceived. Their cues described linear in- and decrease of temperature, almost quadratic pulses at two different temperature ranges and a step-like increase in temperature at two different temperature ranges. The neutral temperature of the device was 30°C and the cues were presented on the tips of two fingers. The patterns were identified correctly between 75% and 85%, with the linear decrease (only cooling) reaching the highest and the linear increase (only warming) the lowest recognition accuracy.

This requirements described the frame in which thermal in-car displays should be operating. Design cue decisions in the research presented in this thesis were informed by these basic observations.

Environmental Influences

The environment can have an influence on the effectiveness of thermal displays. Investigating the influence of clothing on perception and comfort, Halvey *et al.* [51] found that, while the thenar eminence produced the best results, the waist was also identified as a suitable location for thermal feedback with slightly lower detection rates, but similar detection time,

comfort and intensity ratings. Materials with lower thermal conductivity needed higher temperature changes, but the detection time did not differ and higher thermal conductivity led to a higher number of errors. They also found that higher extent of temperature change was perceived as more comfortable with clothing between the device and the skin and the higher perception rate of cool temperature changes found in previous studies could not be observed with clothing.
In further studies, Halvey *et al.* [88] explored the influence of ambient temperature and humidity on detection and perception of thermal cues. They tested stimuli at outdoor locations in varying weather conditions over five months. The best results in terms of detection rate (84%), detection time (3.03s) and comfort ratings was achieved for temperatures between 15°C and 20°C. However, results at other ambient temperatures still indicated suitability. Humidity only had a significant influence on detection rate, time and comfort ratings for extreme conditions. Wilson *et al.* [89] found that ambient temperatures significantly effected identification accuracy and time. They pointed out that there were high individual differences, but on average the identification worsened when the ambient temperature was warmer (between 25°C to 26°C).
Ketna & Leelanupab [27] investigated thermal feedback in noisy and bumpy environments. Audio and vibrotactile cues are often sought as alternatives to visual feedback, but have been shown to perform poorly in noisy and bumpy environments, respectively. They tested unimodal thermal and multimodal cues including thermal and found that the detection of thermal cues was not influenced by either noise or environmental vibration. In multimodal cues, thermal feedback enhanced detection.

The in-car environment presents many possibilities for locations on which to present thermal feedback and can be bumpy and noisy by nature. Other environmental parameters can easily be controlled within the well-defined area of the vehicle cabin and pose no concern for the use of thermal feedback within the car. This previous research showed that thermal feedback through clothing could be detected and its detection was not influenced by noise and a bumpy environment, showing its suitability for the in-car environment. However, as detection through closing needs some more research into suitable adaptation, this thesis will focus on the presentation of temperature changes directly on the skin.

Thermal Hardware

Some characteristics of thermal displays are particular to the method used to present temperature changes. Peltier devices are the most often used thermal devices. They are thermoelectric devices, warming one side of a plate and cooling the other, depending on the direction of the current. Cooling one side of the device, therefore, leads to the need of dissipating hot temperatures on the opposite side. This is usually achieved by adding a heat-sink (see Fig-

Figure 2.3: Peltier device (white) attached to heat-sink (black).

ure 2.3), water-cooling system or alternatives. Extent and rate of temperature change depend on the direction and magnitude of the current [90].
Kratz & Dunnigan [91] used liquid cooling and electro-resistive heating for a grid device, instead of Peltiers. This setup was only practical for at least semi-stationary use and further work would have to be done to achieve precise temperature output. However, the setup is more easily scalable than grids with Peltier devices would be, as those need a lot more energy.
Nakajima *et al.* [92] used light and mist beams to produce mid-air thermal sensations, specifically to reproduce the Thermal Grill Illusion. This method needs a larger setup than Peltier elements and precise temperatures are hard to generate.
Hirai & Miki [93] designed a thermal device which changes the thermal conductivity of its surface to evoke different tactile sensations, rather than the present temperatures directly. The device varies by filling or emptying cavities under the surface with liquid metal. This method closely simulates the thermal sensation when touching and identifying an object and could enhance the experience in virtual environments.
Brooks *et al.* [94] used a different approach to illicit the feeling of warm and cold in VR: they presented smells associated with thermal sensation, namely eucalyptus (mint) for cold and chilli peppers for warm sensations, and presented them directly under the nose. They managed to produce simple warm and cool sensations with this setup, without the need to warm or cool participants or the environment and with comparably low energy demand. In addition to smell, taste sensations can be associated with temperature: presenting thermal feedback on the tongue can elicit taste sensation [95].

The most used and fastest thermal devices in previous research are thermo-electric Peltier devices. Temperatures can be presented precisely with appropriate control mechanisms and were, therefore, chosen to be used for the research presented in this thesis.

Summary of Thermal Displays

Research of thermal displays and thermal cue design suggests that temperature changes of 1°C/s and 3°C/s could be well recognised. Base temperatures between 30°C and 32°C were suitable for temperature changes up to 6°C. Temperature changes, rather than discrete temperatures, were detected and the thenar region was confirmed as the most suitable location, but finger tips were also successfully presented with thermal cues. Direction of temperature change was identified as the best recognised factor of thermal design, but rate of temperature change and extent of temperature change in combination had promising recognition rates. Thermal feedback was well recognised in a noisy and bumpy environment, but ambient temperature influenced recognition.

2.2.2 Affective Computing

Affective computing describes the interface of computing systems and emotions. For thermal feedback, affective computing is achieved by enhancing a system with thermal capabilities to present or manipulate emotions.
Research has shown that temperatures can influence or represent social presence, where colder temperatures are linked to exclusion [96] and warmer temperatures to interpersonal *warmer* judgement of personality, such as being more generous and caring [97] and increased social proximity [98]. This relationship can be easily observed in descriptive language, where *icy stare* and *cold shoulder* have negative connotations, while *warm smile* and *hot date* tend to be interpreted positively.
Feedback in the car could potentially benefit vastly from affective associations, as it could create more easily understandable cues, conveying complex messages non-visually. The following section will discuss several areas in which affective associations have been investigated. The mapping of emotion to cue is dependent on the use case, so several different areas could potentially provide interesting mapping contexts for in-car communication. First, more abstract mappings will be discussed, followed by a number of areas in which thermal cues have been used to provide emotion-based feedback.

Abstract Mapping to Arousal-Dominance-Valence

Emotional responses to thermal cues have been tested and it was found that warm temperature changes increased dominance and arousal [99] and were rated as pleasant for a change of 4°C, but unpleasant for 6°C [100]. Emotional valence (positive/negative) was found to

mirror the use in language: warm was linked to positive and cold to negative [101]. A study investigating arousal and valence found that they were linked: ratings were found either in the low arousal/high valence quadrant (calm/pleasant) or in the high arousal/low valence quadrant (excited/unpleasant) [43]. Warm temperatures were rated more pleasant and their arousal increased with higher extent and rate of temperature change.
Tewell *et al.* [102] tested an array of thermal devices and influenced the arousal of an incoming text message by presenting temperature on a differing number of devices, valence was influenced by the content of the message. They found that warm temperatures were perceived as more arousing, but did by itself not give any valence information.
Wilson *et al.* [103] mapped emotional responses to multimodal cues, with thermal, vibrotactile and visual modalities. They generated several *lookup tables*, showing which combinations of modalities could potentially convey specific emotional sensations and defined guidelines based on their findings. The combination of several modalities was helpful to increase the range of emotions and they found that the overpowering effect of vibration could be tempered by the addition of other modalities. Presenting three cues together could, however, be perceptually taxing on the senses. Vibration mostly influenced perceived arousal, while thermal or visual feedback influenced valence.

These findings inform on general reactions of temperature changes on abstract emotions, independent of use cases. They were used to form expectations for affective associations within specific use cases.

Providing Affect for Communication

More specified thermal feedback was used to enhance communication with emotional meaning. Iwasaki *et al.* built the AffectPhone [104], a prototype attached to a mobile phone, which measured the galvanic skin response (representing the emotional state) of one communication partner and presented the corresponding temperature to the other.
A prototype, sending thermal messages remotely between either mother and daughter or two co-workers, was tested by Lee & Lim [48]: one partner could send thermal messages to the other by pressing buttons. As before, warm temperatures were linked to more positive and cold to more negative feelings, with varying degrees depending on the extent of temperature change, but the interpretation of the temperature was context dependent. The feedback was experienced as non-obtrusive and playful.
To increase the feeling of social presence during messaging, Gooch *et al.* [105] built a thermal harness to simulate a thermal hug. They found that the added thermal cue showed an increased sense of presence, but could not prove that the increase could be attributed to the feedback or the context of use.
Another study by El Ali *et al.* [106] investigated thermal stimuli on the chest, enhancing

(neutrally-spoken) voice messages with affect. They found that the stimuli could be well perceived through the fabric and warm and cool cues increased arousal and increased (warm) or decreased (cold) valence of the message.
Suhonen *et al.* [107] investigated three different haptic modalities and their influence on interpersonal communication: thermal, vibrotactile and squeeze feedback. Squeeze feedback was achieved by tightening a wristband in varying patterns. In contrast to other previously discussed research, participants experienced cold temperature changes as more pleasant. Squeeze feedback was received positively and both squeeze and thermal feedback were connected to everyday notifications, for which vibration is already used. Haptic feedback was described as efficient and intimate, adding a rich, new dimension to communication. A similar setup tested by Song *et al.* [108] looked at identification of squeeze and thermal cues and compared them to vibration. They found that squeeze feedback could almost be identified as reliably as vibration, but the perception for thermal feedback was poorer.
Osawa & Katsura [109] discussed a thermal glove set that mirrors the thermal sensation of one glove onto the other, with potential use cases in remote care or robot interaction. Peña & Tanaka [110] went further and prototyped a robot with thermal capabilities in the skin. Investigating the effect of thermal skin on a robot, Park & Lee [111] found that warm skin temperature increased social presence, perceived friendship and perceived emotional stability.

Within the vehicle, feedback is given to communicate information to the driver. These findings on enhancing communication with emotions could be used to add an additional, easy to understand layer to the communication between car and driver. In this thesis, thermal feedback was used for notifications, looking into how the thermal feedback can increase the feeling of urgency, which was believed to coincide with the increase of arousal found in this previous research.

Enhancing Media with Emotions

The emotional interpretation of media, such as pictures and videos, can be very subjective. Artists could potentially use thermal feedback to guide the observer and convey their intended emotions.
Or they could assign specific temperatures to locations within pictures, as did Nakashige *et al.* [112]. They designed a thermal trackball, which changed the temperature when the cursor touched parts of a picture that were linked, such as a bowl of warm soup or cold orange juice. Participants rated pictures of dishes as more delicious, when the matching temperature was presented and reported emotional associations such as a *loving home* with warm soup.
When exploring different aspects of thermal augmentation of pictures, Akazue *et al.* [46] found that the timing of thermal presentation can either create anticipation or increase the

emotion of the presented picture. Furthermore, they found that the presented temperatures increased valence and arousal in pictures with low valence and arousal and decreased the two factors for pictures with high valence/arousal.
Looking at both pictures and music, Halvey *et al.* [42] found that valence and arousal were influenced by thermal cues for both visual and auditory media, where thermal feedback generally enhanced arousal. Their results suggested that thermal feedback adjusted to the content of the media, might have a more pronounced influence, which should be investigated further.

This research found very precise mappings of emotional associations and temperatures. Warm temperatures invoked a feeling of *home* and could increase the emotion of presented content. This specific associations informed the use case design of thermal notifications within the thesis.

Other Use Cases

As affective interpretations are context dependent [48], the design of temperature feedback has to be adapted and tested for specific use cases. Wilson *et al.* [113] explored a number of different application areas of thermal feedback and captured reactions and interpretations. In their experiment, they presented temperatures as indication of online activity of phone contacts, physical presence and availability of a person with thermal cues on the door knob, content use before deletion and restaurant ratings. They found that participants generally agreed on the meaning of the presented stimuli. They interpreted warm temperatures as a representation of presence and attributed positive emotional impressions, while cold represented absence of people and activity and presented negative emotions. Up to seven different levels of temperature were labelled within each application. In the case of the door knob, warmer temperatures were interpreted as the person being in the office, with increasing temperature indicating a higher level of business. In the content deleting task, participants were shown the potential risk of deleting data by showing thermally how much it was used beforehand. Warm temperatures again were identified as being used frequently and, therefore, posing a higher risk when being deleted.
This idea of using temperature to present risk or danger was picked up and used for studies investigating the benefits of using thermal feedback to inform of the security of web pages [49]. The idea was first explored in an online questionnaire, where associations were collected. Participants mostly correlated warm temperatures with secure web pages and cold with insecure web pages. This was followed up with a lab study, which found interpretations inversed: secure web pages were associated with *very cold* temperatures, while insecure web pages to *very warm*. Participants commented on an association of heat to danger and cold with calm. Napoli *et al.* [114] adopted this to inform on the security of TLS certificates. They built a prototype using a heating pad on the laptop, presenting temperature on the wrist,

which needs additional evaluation to determine its usability.
Lately, thermal feedback was used to help users assess their own body's reaction, by projecting internally sensed temperature to a thermal waist belt [41] or by notifying users about stress [115].
Umair *et al.* [116, 117] used thermal feedback in connection with self-crafted worn smart artefacts to support the wearer's awareness of their own state of arousal. They discussed the materials used and described several stages of the crafting process. Participants had the chance to play around with different heating devices and some of their comments were shared. Participants commented negatively on their lack of controlling the return to neutral temperatures in the heating pads. Peltier devices were also used, but only one-directional with providing current to heat up and then letting them cool passively by removing the battery.
Trojan *et al.* [118] investigated, if the rubber hand illusion could also be induced by visual-thermal stimulation. The rubber hand illusion traditionally is induced by touch: the real hand of participant, obstructed from view, and a rubber hand placed next to the real hand are repeatedly touched at the same time. This leads to induced feelings of ownership of the artificial hand, as if the hand were part of the participant's body. The same effect was observed when coloured spots were presented on the rubber hand and a thermal cue on the real hand, especially when the colour *matched* the temperature: warm/red, cold/blue. This effect could potentially be used to increase immersion in virtual reality.

The research presented in this section discussed a number of different, specific use cases for which thermal feedback was investigated. It can be seen that the interpretation of temperature is very use case dependent. The act of actively feeling the temperature change could also change a perception participants had when interpreting them theoretically, as shown in the case of the security of web pages. These findings showed that expected interpretations have to be experimentally proven, an approach which has been used for the research of this thesis. Furthermore, the idea of presenting danger in this previous research inspired the use case of notifications with different levels of urgency with thermal feedback within the thesis.

Summary of Affective Computing

Thermal feedback can evoke emotional responses. The direction of temperature change was in general associated with valence: warm temperature changes were interpreted with positive, cold temperatures with negative emotions. However, in specific use cases, these mappings were reversed. When the cue was associated with security, warm temperatures were connected to the feeling of danger, while cold represented security. In other areas, such as interpersonal communication, warm cues represented familiarity and social presence. The interpretation of thermal cues is context dependent and new use cases have to be tested to ensure that the intended meaning is communicated. However, when the association was made, the effect was quite consistent within participant groups.

2.2.3 Virtual Reality

One of the areas in which thermal feedback has been used the most, is Virtual Reality (VR). The main goal of thermal feedback in connection with VR is to increase immersion, the feeling of presence in the virtual world, by simulating touch sensations or parts of the thermal environment. It has been shown that even the visual representation of thermal cues in the virtual environment without any actual temperature difference in the real world can have an influence on grasp movements [119]. These aspects are less important in an in-car environment, were thermal feedback would be used to convey information, rather than aim to enhance any kind of immersion. Therefore, only a comparatively short overview will be given of thermal feedback in VR. As one of the areas with increased research in thermal feedback, examples from this area might be briefly discussed in other sections.
Research in this area often investigates effective delivery systems for temperature feedback, which would not interfere with the activities usually performed within VR. To this end, most commonly gloves or hand-worn devices were outfitted with thermal, and often other tactile, devices [33, 70, 120, 38, 34, 39, 121], parts of clothing fitted with thermal capabilities [37] or VR equipment enhanced [122, 123]. More rarely, the physical environment gets adapted to simulate the virtual environment [124].
Use cases vary, but most commonly thermal feedback was used to represent the virtual thermal environment [35, 122, 36, 125, 37], or object temperature for identification [126, 70, 38, 39, 34, 127]. More exotic use cases involve creating sensations in VR that are not possible in real life, such as the feeling of passing through an object [128].

This short summary of thermal feedback within VR was added because it is one of the most used applications for thermal feedback within research and should be mentioned at least briefly for a complete discussion of thermal feedback. The goal of the use cases within VR differ significantly from in-car feedback for drivers, but might be interesting when investigating the use of temperature within the car for passengers, especially in view of automated vehicles.

2.2.4 Stationary and Mobile Application

This section will introduce some thermal displays with a setup fixed to a single location, either because of their bulky shape or because their function connects to a specific location. Feedback in the car combines aspects of stationary and mobile applications. While the setup

inside the cabin is comparable to a stationary setup, the movement of the car adds requirements of mobile environments, such as the need to be aware of the surroundings. Therefore, both stationary and mobile applications will be discussed.
Kushiyama *et al.* [129] used a large array of Peltier devices to present or enhance pictures with temperature. They did not primarily aim to add a layer of affect, as in research discussed previously, but used this setup in collaboration with artists to allow them to add the layer of touch to their art. In further steps [130, 131], they used their setup with thermally sensitive sheets, changing their colour depending on temperature. These sheets would visualise the temperature of the Peltier devices under it, thus producing images which can be both seen and felt.
Thermal feedback on game controllers were investigated [132, 133]. Comparing visual, vibrotactile and thermal feedback for finding elements in a game, Löchtefeld *et al.* [133] found that while accuracy and time were worse for thermal feedback, it was still effective as an active game element. Thermal feedback was rated as less temporally demanding than both visual and vibrotactile, which could be useful for specific feedback within a game.
Temperature was also used to navigate a two dimensional maze game [134], where the feedback was presented on the arm rather than the controller. The feedback would stay warm, while the correct path through the maze was taken and turned colder, when the path was left. Temperature was here presented constantly, eliminating the need to return to a neutral temperature in between cues, only changing when the user left the shortest path through the maze. This feedback helped participants navigate the maze effectively.

Some investigations into design for mobile applications and influence of environmental factors have been discussed in previous sections. This part will focus on research discussing specific use cases or explorations of different locations on the body. Most experiments involve the design of a prototype for use at well defined locations. In contrast, Maeda & Kurahashi [135] designed a wearable prototype of several thermal devices, which could be worn at different locations all over the body and Niijima *et al.* [136] tested a setup with three small devices that held and moved to different locations over the body.
Wettach *et al.* [40] used a handheld thermal prototype for pedestrian navigation through a city. The testing of the device seemed to only have been done with one participant, and they seemed to have fairly intensive training with the device beforehand, as they tested identifying three different temperature steps in one sitting and then long-term over ten days with random stimuli presentations. Training did increase identification of the cues and the participant managed to successfully navigate an unknown city with the device.
Adding thermal capabilities to an intelligent voice-agent device, Kim *et al.* [137] investigated the benefits of thermal feedback to the delivery and enhancement of auditory content and the influence on the perception of the agent. Participants reported that they perceived the voice agent as friendlier when the interaction included thermal feedback. The thermally enhanced

content was noted to be more memorable, when warm temperature was presented, and felt more immersive and engaging.
High identification accuracy was found for feedback on four small cooling elements on a ring-like prototype, especially for single-spot feedback and specific patterns [138]. On the wrist with six different devices and configurations, thermal feedback outperformed vibrotactile feedback in terms of accuracy during walking and in distracted situations [139].
Thermal feedback on the ear was used to define open space [140]: specific areas in a large open space were associated with temperatures. This can be used to split open space without the use of physical barriers. Observation showed the warmer spots were preferred. Nasser *et al.* proposed thermal feedback on an ear-worn device to provide feedback for hearing and visually impaired [141].

The vehicle cabin can allow for fixed installation of thermal devices. Findings of this previous research suggest that thermal feedback was less temporally demanding than other modalities and could successfully be used for navigation purposes. Both findings inspired the use of thermal feedback for in-car navigation.

2.2.5 Thermal-Vibrotactile Feedback

Haptic displays sometimes combine various modalities for a richer experience and a broader design space [142], which would be of great value within the vehicle. The combination of thermal and vibrotactile feedback has been explored in some detail, as the fast onset and detection of vibration as opposed to slow, but more emotionally interpreted thermal cues combine two very different experiences of touch. In VR, thermal-vibrotactile feedback could lead to even more immersive experiences. For example, when simulating holding a cup which gets filled up with cold water, thermal feedback could present the temperature of the water, while vibration could simulate the impact of the liquid within the cup [143].
The two modalities presented together can, however, influence their perception. Some of the affective influences were already discussed in Section 2.2.2. The perception of vibrotactile feedback differed for high frequency voltage cues: perception thresholds were higher for cold than for neutral and warm temperatures [144]. Skin temperature also had an effect on the identification accuracy of vibrotactile patterns. Warm skin aided the identification of vibration patterns with varied amplitude, while it hindered the identification of patterns with varied pulse duration [145].
In reverse, the number of vibration pulses can influence the perception of thermal patterns [30]. Perception of cold cues was found to be more heavily affected by concurrent vibration than warm cues.

These findings inspired and informed the use of bimodal tactile feedback for notifications presented in this thesis. Three experiments investigated temperature changes in combination with vibration, each of which used different onset times for the modalities.

2.2.6 Temperature in Driving

In a vehicular environment, temperature was mostly discussed in terms of thermal comfort assessment and prediction models [146, 147, 148, 149]. Another focus lies within counteracting driving fatigue with thermal changes [150, 151]. It has been shown that 4min of cooling can mitigate driver fatigue. In these instances, the whole cabin and driver were subjected to temperature changes. While it was suggested that more localised cues at the hands might be effective and should be tested to counteract driver fatigue [152], using thermal cues for information purposes in a vehicular environment has not been tested. This thesis aims to fill this gap.

2.2.7 Summary

Thermal feedback possesses some unique characteristics, which suggest its use for many very different applications. In VR, its contribution to identify materials is interesting, as is the enhancement of the feeling of immersion when simulating temperatures either of the surroundings or interacting objects.
Affective associations play an important role both in- and outside of VR: warm temperatures were generally associated with positive, active and personal experiences, cold with negative, inactive, and distant ones. But warm can also increase the feeling of danger or insecurity, and the experience of feeling it can lead to different interpretations than were expected when contemplating them theoretically. The mapping of thermal associations can be delicate and needs to be tested for specific use cases. But when they have been found, they generally were interpreted consistently across participants. For the driving environment, interpretation of direction or danger are of special interest. In terms of navigation, thermal feedback was used to direct users by presenting warm temperatures while they stayed on the correct course and cool when they left it. This interaction cannot be adopted for driving, as turning around might not always be possible or potentially dangerous. Turn-by-turn navigation would be more effective and different approaches on feedback will have to be tested for that.
Investigations of the design space of thermal feedback showed that 30°C to 32°C as neutral temperature in between cues was suitable. Rate of change should be faster than 0.3°C/s, and 1°C/s and 3°C/s have been identified as effective. Thermal changes of 3°C and 6°C could be distinguished well in both directions, smaller changes were harder to detect. The thenar eminence was affirmed as the best location for thermal feedback on the hands, but cues on the fingers could be detected and distinguished as well, especially when presented on several fingers. Detection of warm and cold stimuli can differ significantly, especially

when presented simultaneously with vibrotactile feedback. These findings highly influenced the design of thermal cues within this thesis.
These are important basics for designing thermal cues for the driving environment. However, the environment in which these cues will have to be identified, are very different in nature. While environmental factors are less of an issue within cars, as the thermal environment can be measured easily and any feedback potentially adapted, identification and perception of thermal cues will be moved from a primary task, as it has been in most of the studies discussed in this section, to a secondary task with a highly demanding primary task. The increase in workload and actions done simultaneously during driving could have a distinct influence on perception and identification of thermal feedback. The following sections will focus on factors of driving and haptic feedback during driving.

2.3 Driving Background

This section delivers some background information on important issues of designing feedback for the driving environment. Driving is a highly demanding task, in which mistakes can lead to grave consequences or even death. There are many demands posed onto the driver, including the need of high situation awareness [153] to ensure the safe operation of the vehicle within its environment. When designing cues for use during manual driving, it is important to distract the driver as little as possible from their main task.

This section will first discuss driver distraction and its important role in evaluation of in-car applications. This will be followed by a brief overview of levels of autonomy and the change in demands on driver attention and driving.

2.3.1 Driver Distraction

Many different definitions of driver distraction can be found. Driver distraction is generally described as a subset of inattention [153, 154], where the attention is diverted from the driving task by another activity, as defined by Lee *et al.* [155, 156]:

> *Driver distraction is a diversion of attention away from activities critical for safe driving toward a competing activity.*

The *activities critical for safe driving* are less well defined. Typically, driving related activities are described as primary, driving unrelated activities, such as eating or operating mobile

devices, as secondary tasks. The primary driving task includes driving manoeuvres, longitudinal (velocity) and latitudinal (lane keeping) control of the car and staying aware and reacting to traffic regulations and participants. Generally, everything outside this scope is counted at least as secondary task. The categorisation of tasks such as navigation, however, are not always clear. Navigation cues are often integrated into the in-vehicle infotainment systems (IVIS), which is in general regarded as providing secondary tasks [157, 158]. However, navigation is time and location specific and not always optional and could be considered driving related and, therefore, is sometimes included into the primary task [159, 158]. Secondary task distraction has been associated with the highest percentage of crashes in an extensive naturalistic driving study [160, 2].
The categorisation by the National Highway Traffic Safety Administration (NHTSA) is often applied to the discussion in how attention can be diverted [154]:

> ***Visual distraction:*** *Tasks that require the driver to look away from the roadway to visually obtain information;*
> ***Manual distraction:*** *Tasks that require the driver to take a hand off the steering wheel and manipulate a device;*
> ***Cognitive distraction:*** *Tasks that are defined as the mental workload associated with a task that involves thinking about something other than the driving task.*

Some definitions include auditory distraction in this listing, such as Pettitt *et al.* [161], who comprised a more precise and detailed definition of driver distraction, including the different possible types of distraction:

> *- Delay by the driver in the recognition of information necessary to safely maintain the lateral and longitudinal control of the vehicle (the driving task)* ***(Impact)***
> *- Due to some event, activity, object or person, within or outside the vehicle* ***(Agent)***
> *- That compels or tends to induce the driver's shifting attention away from fundamental driving tasks* ***(Mechanism)***
> *- By compromising the driver's auditory, biomechanical, cognitive or visual faculties, or combinations thereof* ***(Type)****.*

The presentation of thermal feedback could possibly present cognitive distraction from the main driving task, posed by the thermal devices within the car, and could have an impact on the driving behaviour.

The measurement of distraction is often based on the influence of the distraction on the driving behaviour (performance based data) and/or the driver's behaviour (physiological

data) [162]. Hurts *et al.* [157] and Riener *et al.* [163] summarised methods mostly used to examine a task in the context of the primary driving task. Some methods are about measuring task-related data, such as task completion time, errors and response time.
Others observe physiological data, such as number of gazes needed to complete the task and the gaze time as well as overall eyes-off-the-road time. Visual distractions, which averts the gaze from the forward road, pose the highest risk of resulting in crashes [2, 164], especially when glances are longer than 2s [2].
In addition, the impact on the longitudinal and lateral control can be evaluated. Longitudinal control is typically measured by evaluating speed (mean speed, speed variance and/or speed compliance) or headway (and/or headway variance). Lateral control is usually measured through investigating the lateral position (or lane deviation), using either the standard deviation of the lateral position, lane exceedance or the root mean square error of the lane position [165]. Eyes-off-the-road time can significantly increase lane deviation [166].
Another suggested method investigates the miss rate and mean response time of the peripheral detection test (PDT), where items are presented to the driver in their visual periphery. As workload increases, peripheral awareness decreases, as the visual attention narrows [167, 168] and higher miss rates and longer detection times can be used as reliable indicators of driving distraction.
Measuring mental workload is another method to capture driver distraction [162, 169]. High mental workload can have an influence on the driving performance, as it can increase lane deviation [168]. The NASA task load index (TLX) questionnaire [170] was designed to capture self reported subjective workload. It captures six aspects of workload: mental demand, physical demand, temporal demand, performance, effort and frustration. An additional scale for *annoyance* has occasionally been added in the past [171].

The impact of a secondary task on the workload can be mitigated to some degree by using different modalities than those engaged in the primary task. This was suggested in the Multiple Resources Theory [3], which proposes that a more even spread of information over different sensory resources could help decrease mental demand. Wickens' theory presents three different dimensions that influence the performance in concurrent tasks: the *stages of processing* (Perception and Cognition / Responding), the *codes of processing* (Spatial / Verbal), and the *modalities* (Visual / Auditory). The theory suggests that *the extent that two tasks use different levels along each of the three dimensions, time-sharing will be better* [3], which in turn would lead to a better driving performance and less mental workload. A fourth dimension *visual channels* (Focal / Ambient) was added as an expansion of the original model and while the model primarily discussed the visual and auditory channels for the dimension *modalities*, the expansion including other sensory channels have been discussed [172] and appear to be widely accepted.
Driving engages primarily the visual and kinaesthetic sense [157]. Kinaesthesia describes

the perception of position and movement of limbs, and often includes force perception [173]. Secondary tasks should, therefore, be designed to address other senses.

Typically, the distraction of a secondary task or newly designed feedback is measured during simulated driving, as it allows to precisely control many aspects of the driving environment, leading to similar and repeatable scenarios and the possibility of presenting dangerous situations without the risk of injury [174].
The influence of thermal feedback would mostly be of cognitive nature. Changes in driving behaviour, captured by example with lane deviation, and perceived workload ratings were chosen to determine the level of distraction posed by thermal feedback.

2.3.2 Autonomous Vehicles

Autonomous vehicles are expected to outnumber manual vehicles in the near future. The change has already begun, with many cars already being outfitted with features that can take control over driving aspects, such as lane keeping assistants, which take over lateral control of the car. The Society of Automobile Engineers (SAE)[1] has devised a categorisation of autonomous cars (see Figure 2.4[2]), which has become a reference point for discussion and research. The different levels of automation will be shortly discussed here.
Level 0 is driving without any kind of automation involved, depicting classical manual driving. The car can give warnings and momentary assistance, for example lane departure warning or automatic emergency braking.
In Level 1, *Driver Assistance*, the driver transfers the control of one specific task to the car, for example velocity control or lateral control, but the driver can interfere at every point and has the obligation to do so in dangerous situations. Examples for this would be lane centring or adaptive cruise control.
The next level sees two functions transferred to the system at the same, while the driver is still being expected to be available at any time and is supervising the system. This is called *Partial Automation* and would be achieved, for example, when both the lane centring and

[1]https://www.sae.org/news/2019/01/sae-updates-j3016-automated-driving-graphic (accessed 09/2020)
[2]https://www.nhtsa.gov/technology-innovation/automated-vehicles-safety (accessed 21/09/2020)

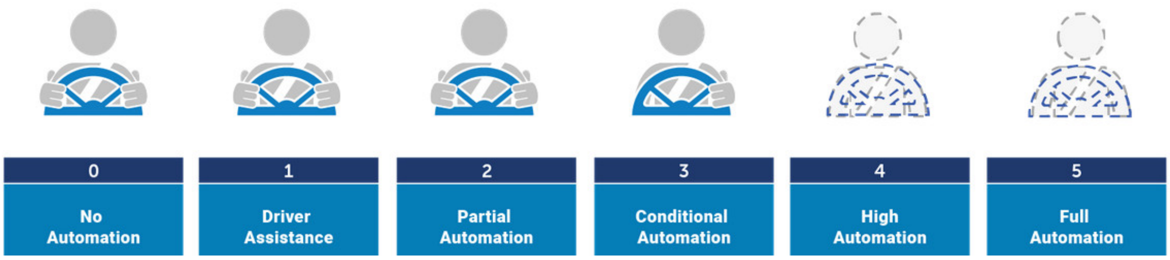


Figure 2.4: SAE Levels of Autonomy.

adaptive cruise control were activated at the same time.
The Levels 0 to 2 describe driving situations in which the driver is in charge of the car, being expected to take full responsibility of the driving performance.

Level 3, *Conditional Automation*, is described as the state in which all driving tasks are fulfilled by the car, but the driver has to be available for taking over control when needed. An example feature for this is a traffic jam chauffeur, which can take over lateral and longitudinal control during a traffic jam.
Level 4 addresses *High Automation* situations in which the car is able to drive fully autonomous under certain conditions, such as specific areas with local driverless taxis.
The last level, *Full Automation*, describes a state in which the car takes full control of the driving task and the driver is not expected to be available at all.
In Levels 3 to 5 the car is in control of the driving, but in the lower Levels 3 and 4 the driver can still be involved. Situations in which control might have to be transferred between car and driver can, therefore, occur in vehicles with conditional and high automation. The transfer of control can be distinguished between *handover*, when the driver hands the control to the car, and *takeover*, when the driver takes back control from the car. These situations can be driver-initiated or car-initiated (system-initiated) and scheduled or non-scheduled [175, 176]. Research is highly focused on takeover scenarios, especially takeover in emergency situations. These takeover requests would only occur when the car has either detected a dangerous situation it cannot resolve on its own or the car has diminished situation awareness due to loss of sensor information because of damage or extreme environmental or weather conditions. In either case, it is paramount to inform the driver rapidly and effectively on potentially upcoming danger, as well as traffic situation and vehicle state. Section 2.4.3 will discuss research on using haptic feedback to aid the transfer of control.

The location of and potential use cases for haptic feedback for vehicles with autonomous features depends on the level of autonomy. Haptic feedback on the steering wheel would only be effective for Levels 0 to 4, with limited use cases for Levels 3 and 4. Feedback on other locations, such as the seat or seat belt, could be used in any level of autonomy. As the thesis focuses on presenting thermal feedback directly on the skin, interaction will be investigated only for vehicles within the first 4 autonomy levels.

2.3.3 Summary

Driving is a highly visual primary task, which imposes many demands on the driver. Secondary tasks can compete with the resources engaged in safely manoeuvring the car and are one of the major contributors to crashes. Visual distraction with high eyes-off-the-road time are especially risky. Engaging other senses with a secondary task can mitigate this effect not only by leaving the visual channels open for the primary task, but also by decreasing mental workload. Haptic feedback can be used as one of those alternatives. Eyes-off-the-road time is a widely used measure to evaluate the impact of a secondary task on driving, but this measure would be not very insightful when that task does not involve any visual elements. Mental workload would be a more appropriate measure to explore the influence of a haptic modality such as thermal feedback on driving. Perceived workload can be easily measured with questionnaires, such as the NASA TLX. This can be only applied when the questionnaire can be presented after being exposed to a single type of feedback. Another commonly used measure is lane deviation, investigating the influence of a secondary task on the driving performance. There are several ways to measure this factor, one of them being the Root Mean Square Error (RMSE) of the lane deviation. In addition, task performance of the secondary task is used to evaluate the effectiveness of the task and the posed distraction.

When investigating feedback for autonomous cars, the moments during and shortly after control is transferred from driver to car (handover) or car to driver (takeover) are of special interest. These control transfers can occur in cars with automation levels 3 and 4 and initiated by either driver or system. The next section will discuss research on haptic feedback used in the car. Before summarising practical applications during transfer of control, more common application areas will be discussed: haptic feedback for navigation and notification purposes in the car.

2.4 Haptic Feedback for In-Car Applications

The section discusses haptic feedback within the vehicle environment. Haptic describes in general both kinaesthetic and tactile stimuli [177]. As discussed before, the kinaesthetic sense tracks body movements and is highly engaged during the driving task. In the driving environment, torque feedback is the most often used kinaesthetic feedback. Torque is typically embedded into the steering wheel, where forced movements or jerks of the steering wheel are used to convey warnings or aid lateral control [178, 179, 180, 181, 182, 183, 184, 185, 186, 187]. Some force feedback can also be found on pedals [188]. Tactile cues involve stimulation of the skin. This cutaneous stimulation can be achieved through mechanical, chemical, electrical or thermal cues [177]. The presentation of thermal feedback will be more closely related to the presentation of other tactile cues in the car and the discussed research in this section will, therefore, focus on tactile feedback.

There are several classes of information in cars that could potentially be conveyed with haptic feedback [189]: spatial information, warning signals, communication (of driving related information), coded information (mostly abstract presentation of car state information) and general (such as guiding during use of the dashboard). These different kinds of cues can be presented on a number of locations in the vehicle environment: seat, seat belt, steering wheel and pedals. Touch-less tactile sensations such as air streams [190] or ultrasound [191] can be presented on any part of the body, even though the sensation might be hindered by clothing. Vibration is one of the most widely investigated tactile feedback types. Outside of the car, exploration of vibrotactile feedback led to guidelines [192, 193, 194, 195, 196, 197] and design explorations [198, 199, 200, 201, 202]. Within the in-car environment, possible locations have been tested for abstract identification and design (seat [203, 204, 205, 206], seat (or waist) belt [207, 31, 208, 209], steering wheel [210, 211, 212], pedals [213, 214, 215, 216]) and compared for different use cases [217, 218, 219]. Literature on haptic in-car feedback is vast and a detailed discussion would be out of scope of the thesis. Therefore, three specific and often applied use cases will be discussed. Section 2.4.1 *Navigation* will discuss directional information for lane changes and turn-by-turn navigation. Section 2.4.2 *Notifications* will summarise warnings and notifications to the driver and Section 2.4.3 *Transfer of Control* will focus on haptic interaction for autonomous vehicles.

2.4.1 Navigation

Haptic pedestrian navigation systems usually work with vibrating wearable [220, 221, 222, 223] or mobile devices [224, 225, 226, 227, 228]. Vehicle types other than cars, such as motorcycle [229], helicopter or boat [230, 231] often presented vibrotactile navigation cues on the waist or thigh belt [232]. In the car, waist bands, mostly to simulate or substitute seat belts [233, 8, 9], seats (with cues under the thigh [6, 7]) and steering wheels [10, 234, 11, 12, 235] have been used to convey vibrotactile navigation information. Alternative tactile modalities, such as shear or stretch feedback, were more commonly presented on the steering wheel [13, 236, 14], but could also be presented on the seat [158].

In the car, spatial information for haptic navigation was generally presented by feedback position: the side of the driver's body on which the cue was presented indicated the direction of the intended lane change [10, 13, 11, 7] or turn [189, 6, 233, 8, 12, 235, 158]. Sometimes, the explicit information *go straight* was added to the tactile dictionary, typically with a dynamic activation of several actuators in a forwards direction [189].

When vibrotactile cues were presented on the steering wheel, a balance of vibration intensity had to be struck: the vibration had to be intense enough to be felt on the hand, but needed to be subtle enough to keep the whole steering wheel from vibrating to ensure one sided cues could be identified [10].

Some tactile displays presented the direction information with dynamic patterns. Hwang *et al.* [11] embedded 32 actuators into the steering wheel and tested vibration patterns, evoking tactile illusions. Their findings showed that vibration on a single actuator in progression along the steering wheel towards the turning direction, invoked the sensory saltation illusion (as discussed in Section 2.1.3) and had the highest recognition rate and fast response times.

With 20 vibrotactile actuators, Kim *et al.* [235] used clockwise activation on the right steering wheel side for right, and counterclockwise activation on the left side for left turn instructions, again counting on sensory saltation to enhance the feeling of directional motion. In pilot tests, they compared tactile feedback to audio and visual feedback and all combinations thereof and found that the multimodal conditions had better preference ratings and performance and less cognitive load than single modality feedback. A follow-up study with multimodal feedback compared navigation of elder and younger drivers. They found that elder drivers were less impacted by visual presentation of feedback than younger, but had higher workload in every condition. Younger drivers preferred the visual-auditory presentation, already known from conventional navigation systems, but feedback including haptic cues performed better and faster. For elder drivers, the combination of audio and haptic feedback worked best.
Studies showed that vibrotactile cues reduced navigation errors in situations with auditory noise or distraction [12]. Additionally, in cognitively demanding navigation tasks, reaction times were shorter for non-visual feedback and haptic was rated as less physically demanding than audio and visual. While the error rate was highest for haptic feedback, ratings still showed participants preferred vibration [7]. In situations with high workload, tactile navigation reduced workload compared with visual navigation. The multimodal combination led to fastest reaction time [6].

Some studies investigated how the factor distance could be encoded into vibration. The factors rhythm [189, 6], intensity and duration of vibration pulses (or combinations of them [233, 237, 8]) have successfully been used to convey distance information. In addition, more complex turning scenarios, such as roundabouts have been considered and successfully navigated [12, 8].

Few tactile non-vibrotactile feedback types have been tested for directional cues in the car. Medeiros-Ward *et al.* [13] presented shear feedback on the steering wheel: actuators under the index finger moved the skin in the direction of the intended lane change. This feedback proved especially effective in situations with audio distraction.
Ploch *et al.* [236, 14] presented skin stretch feedback on the steering wheel: a rotating ring on the rim of the steering wheel was embedded to move clockwise or counterclockwise, stretching the skin along the wheel with its movement. Navigation and second task accuracy were higher for stretch feedback than audio cues.
Rotary motors and vibration actuators on a seat were used for navigation by Farooq *et al.* [158]. The vibration was used to catch the driver's attention, while the direction of motor rotation indicated the turning direction. The degree of rotation encoded information on how sharp the upcoming turns were and could even prompt U-turns. Secondary task performance was faster in the haptic and audio condition than visual, but no other differences were found.

Summarising their extensive work on tactile navigation, in and outside of the car, van Erp

& Werkhoven [238] discussed the benefits of vibrotactile feedback (on the torso) and concluded that it can be effectively used for local guidance navigation tasks, independent of the amount of visual load. Furthermore, it can reduce the effect of additional cognitive tasks and be reliably used in the presence of external stressors (such as spatial disorientation and night operations). These findings mirror results of the in-car navigation studies discussed here: tactile feedback for navigation had high recognition rates and in general reduced workload and recognition time, while being less influenced by demanding driving situations and environmental factors. Multimodal feedback including vibration was often preferred and had better performance.

Thermal feedback could be used well for feedback such as navigation, as routes are generally calculated beforehand and the sluggish response of thermal feedback could be easily counteracted by presenting it early enough. The first explorations within this thesis will, therefore, focus on directional cues during driving.

2.4.2 Notifications

This section will discuss notifications presented haptically to the driver. Some of these had informational character, mostly aiming towards increasing situational awareness [239] or improving driving behaviour [215, 240] independent of hazardous situations, but the tactile modality was most often investigated for time critical warnings, such as lane departure [4, 181, 15, 16] or collision warnings [17, 31, 23, 24, 241, 242, 25, 26, 18, 208, 209, 19, 243, 244]. Most tactile stimuli for warnings were vibrotactile, but a system for pneumatic steering wheel alerts was proposed by Enriquez *et al.* [245]: inflatable pads were embedded into the steering wheel, allowing the wheel to pulsate with differing frequencies, leading to faster reaction times.
Shakeri *et al.* [210] provided cutaneous push feedback on the steering wheel: small pins could protrude from the steering wheel to poke the palm of the driver. They tested patterns with differing number of pins and used them to give informational feedback on mid-air gesture input [246, 247].
Situation awareness of rear obstacles could be increased by presenting them haptically with servomotors in the back of the seat [239]. This led to a shape-change of the seat, presenting obstacles in a continuous way.

Economical driving was encouraged by presenting vibration cues on the accelerator pedal, triggered when the driver exceeded the 50% throttle threshold [215]. This measure resulted in reduced acceleration, both mean and maximum, and excess throttle, in addition to reducing perceived workload. Vibration on the seat or seat belt was proposed to reduce CO_2 emissions [240]. Vibrotactile feedback, on the seat belt especially, led to more fuel efficient driving, even without participants being aware of the purpose of the vibration.

Feedback design of differing levels of urgency investigated audio, visual and tactile warnings [248, 249]. For tactile warnings, the perceived urgency increased with shorter pulse interval. In addition, tactile warnings were rated as more urgent than audio and visual cues, without the high increase in annoyance that could be observed for audio cues.

The influence of speech and tactile feedback on the steering wheel and accelerator pedal for speeding warnings was tested in a simulator study [250]. Warnings of both modalities reduced the frequency of speed violations, but severe violations were only reduced by speech feedback. If speed reduction would lead to safer driving, both modalities performed the same, but vibrotactile feedback was better for situations that needed fast responses. While speech feedback showed an increase in workload, this was not observed for tactile feedback.

When designing warnings, vibrotactile feedback can be used to generally alert the driver, or give additional direction information on the problem. In navigation, the location of tactile cues usually indicated the direction towards which the driver needed to turn. For warnings, however, there are two possible meanings to the position of the cue: it could indicate the direction the driver should steer towards to mitigate the danger, or it could indicate where the danger can be found. Beruscha *et al.* [234] investigated participant's reaction to vibrotactile cues on one side of the steering wheel, once without and then afterwards with instructions. Instructions for two use cases (with and without driving) were presented: when vibration was introduced as lane departure warning, the cue indicated the side on which the car was steering off the lane (steering in opposite direction of cue needed) and in the second case the car was following a line on the road and the cue indicated in which direction to steer to stay on the line. The results of steering without instructions showed no pattern, the direction seemed randomly chosen. During driving, almost half the participants steered toward the vibration, approximately one fourth away and the rest did not steer at all after scanning for danger and not finding anything. The instructed events had less steering errors for the line driving, where the vibration indicated the direction of steering. This suggests that vibration by itself can be interpreted either way, the context decides on how the driver reacts. Suzuki & Jansson [4] had different findings: in their study unexplained vibration of the steering wheel was generally interpreted as lane departure. However, the vibration in their case was not directed, but presented on the whole steering wheel. Lane departure warnings are already implemented in cars and prove useful: an evaluation of police reported crashes found that lane departure warnings prevented crashes of all severities [5].

Research has favoured looking into steering wheel torque over using vibration to warn the driver about an imminent lane departure. Brown *et al.* [16] used steering wheel vibration and directional seat vibration, as well as steering torque, audio and visual cues and no alert. All kinds of alerts reduced the severity of lane departures, but seat vibration did not influence the extent of the departure.

Designing vibrotactile lane departure warnings for truckers to replace often turned off audio warnings, Dass *et al.* [15] presented vibration on the seat as well, both in a simulator test and real world driving. They found that the feedback was as effective as auditory signals and clearly preferred.

Tactile collision warnings have been shown to be unaffected by noise [19] and less affected by conversations [241] with faster reaction times than visual or audio cues [24], and also in combination with visual [243] or audio [25]. Furthermore, the brake reaction time for uni- or multimodal cues with vibration was unaffected by visual orientation [243].
Directed vibration, mostly presented on a waist band, with actuators on the front and back, have led to faster and more correct responses when warning for front or back collisions [17, 31]. Dynamic vibrotactile patterns [208, 209], or multimodal audio-tactile presentation [23], especially when presented from the same direction [242], decreased brake reaction times further.
Multimodal feedback with different levels of urgency, combining visual, audio and vibrotactile cues, have been evaluated by Politis *et al.* [26, 18]. The more urgent cues led to faster responses, as did the multimodal cues compared to the unimodal feedback. Visual feedback slowed response time. Thermal cues, with their inherent association with danger, could enhance the feeling of urgency and in a multimodal setting, where a fast response might be evoked by other modalities and the additional emotional aspect could provide a richer experience.

Many different kinds of notifications during driving have been presented haptically, mostly through vibration and most effectively in multimodal settings. Warnings have been of special interest and could be enhanced with thermal feedback, combining the aspect of multimodality with the advantage of affective associations. The work on feedback with different levels of urgency inspired one of the experiments of this thesis. In addition, the novel cutaneous push feedback, only tested for notification feedback, was chosen as comparison for thermal feedback for navigation, leading to new findings for both modalities. The range of different locations for tactile feedback was adapted for placement of vibrotactile devices for the last experiment of the thesis.

2.4.3 Transfer of Control

This section discusses tactile feedback for the process of control transfer in semi-autonomous cars. Semi-autonomous cars (SAE Autonomy Level 3 and 4) are cars with autonomous features that can take control of the full driving process for specific tasks or under certain conditions, but the control might still have to be transferred to a driver. In these cars the control of the vehicle can be handed over from the driver to the car (handover) or from the car to the driver (takeover). This can lead to situations on the road in which drivers are deeply engaged in a secondary task, while in autonomous mode, and might then need to take over control

of the vehicle without a long adjustment period. If these takeover requests (TORs) were prompted because of a system failure or the car encountering a situation it was not equipped to deal with, an immediate and effective reaction from the driver would be essential. As this is a critical and dangerous situation, research has focused on using tactile feedback to interrupt potentially very engaging tasks [20, 251, 252, 253, 22, 254], give information needed after the takeover and increase situation awareness during takeover [255, 256, 257, 258, 259, 21, 260]. All of these measures ultimately aim to reduce reaction time and increase the quality of driving manoeuvres after takeover and tactile feedback was almost exclusively presented with vibration, generally on the seat [255, 256, 259, 21, 251, 260, 253, 22, 254] or wrist [20, 252], with typically non-directional cues for interruptions and directional vibration (on one side) to present information on upcoming obstacles.
An alternative to vibrotactile feedback to present directional information during the takeover process was presented by Sadeghian Borojeni *et al.* [257] and compared to vibrotactile feedback on the steering wheel. They created a shape-changing steering wheel with plates on both sides, which would be placed under the driver's hands. The plates were attached on a single point in the middle and could rotate the upper part to the left or right, with the lower part moving into the opposite direction. While steering wheel feedback did not decrease reaction times during takeover, vibrotactile (but not shape-changing) feedback led to lower workload.

The investigation of effective interruptions found that vibration (in form of speech tactons) alone were rated as more annoying than in combination with audio or visual feedback. Multimodal cues, designed for different urgencies, were more effective with increasing urgency [20]. When comparing the influence of audio and tactile warning, tactile only led to slower response times, while multimodal combinations with visual and/or audio cues had similar response times [252, 253]. Visual feedback alone had significantly slower response times [251, 252, 253]
Multimodal cues including directional vibration led to faster reactions and increased situational awareness [256, 259, 21]. Basic, static vibration patterns performed better than dynamic patterns, were sets of actuators were activated in succession [255, 260].

Few research has looked into *how* the control was transferred. Transfer mechanisms are generally only mentioned in passing within the study design, detailed discussions are rarely found. Most studies use a single button press [261, 262, 20, **?**, 263, 251, 22] or lever pull or switch [264, 257, 265] to transfer control when the transfer is being actively initiated. Often the use of the steering wheel or brake was enough to transfer control back to the driver [261, 262, 256, 259, 260, 21, 252, 253]. These techniques could easily be done unintentionally, possibly leading to seconds of uncertainty in which the driver is unsure or unaware of who is in charge of driving. Simultaneous double button press [266] could overcome this problem, as it takes conscious effort to press two buttons with two hands at the

exact same time.
Tactile feedback informing on the process itself could further aid to ensure that the driver is aware of the progress and completion of control transfer. Kerschbaum *et al.* [267] proposed a transforming steering wheel, which would very prominently announce the driving state and enhance comfort during the autonomous drive. They tested the concept and participants found no problem with the steering wheel during takeover and reacted faster than in the control condition with a conventional steering wheel. Thermal feedback could also help reassure the driver during the transfer of control, where the temperature change could symbolically present the process of control change.

The slower recognition of thermal feedback would suggest this modality for progress information rather than urgent takeover requests. In combination with vibration, especially on different locations within the car, the bimodal tactile feedback could inform the driver non-visually, lessening the workload. This was explored in the last experiment of the thesis.

2.4.4 Summary

Vibrotactile feedback in the car was generally used to capture attention and effectively achieved this task, as reduced reaction times in most use cases confirm. Spatial placement can guide attention if the context of use is clear, and faster pulse rate of vibration patterns can increase the feeling of urgency of the cue. Multimodal stimuli, adding visual or audio to vibration, often achieved better results than unimodal tactile feedback, though the unimodal variety still outperformed visual only feedback.
Especially navigation information can be effectively presented by other tactile feedback types, such as shear feedback. Thermal feedback could be used in this context as well, as navigation in driving is usually routed and feedback could be timed accordingly, rendering attention grabbing vibration unnecessary.

2.5 Literature Review Conclusions

Thermal displays have recently seen a rise in attention. While one of the most popular uses for temperature is the simulation of virtual thermal environments or objects, thermal cue design has also been explored as feedback for stationary and mobile devices and a number of reliably recognised factors have been identified, best among them direction of temperature change. Thermal feedback has been associated with emotion and different concepts such as danger, familiarity and navigation goals could be linked to warm temperature changes. But still, thermal feedback has not been used in the driving context, even though other tactile modalities, vibrotactile being the most popular, have not only been investigated widely

in research, but have already found their way into modern cars for commercial use. The car presents a closed and well known environment, which could be easily mapped and thermal cues adapted to the thermal environment for optimal use. Vibration is a very attention grabbing modality, but the thermal sense is more sluggish and could be used to present information that does not need immediate attention. Navigational cues and notifications could be encoded into temperature changes and presented on the steering wheel or seat.
As driving is a highly demanding task, any use of new modalities has to be properly investigated and some questions answered. Does the modality have a negative influence on driving behaviour? Is it too cognitively distracting? How well can it be recognised while driving? Does the modality fit the use case? This thesis aims to answer some of these questions.

The research questions posed in this thesis combine aspects of the different sections discussed in this literature review. The complexity and characteristics of thermal sensing (discussed in Section 2.1), in accordance with findings from Section 2.2, will be combined with the specifics of driving related tasks (Section 2.4) and requirements posed by the high demand environment (Section 2.3). Research Question 1 will establish the basic suitability of thermal feedback during driving, by determining if simple binary cues (designed in accordance with [29, 268]) for direction can be used effectively during driving and what influence the presentation of thermal cues has on driving behaviour and workload in a simple driving task, the importance of which was discussed in Section 2.3.1.

Research Question 1: *How accurately can thermal feedback give binary direction cues in an automotive setting (with one thermal device)?*

Adding complexity to both the driving task and the thermal cues, in accordance with findings from Section 2.2.1, Research Question 2 will determine, how suited thermal feedback is for basic in-car applications such as turn-by-turn navigation, when presented with the spatial information of multiple thermal devices on different locations, inspired by tactile feedback research discussed in Section 2.4.1. The comparison with another tactile modality, cutaneous push, was inspired by [246, 210, 247].

Research Question 2: *How accurately can thermal feedback give direction cues in an automotive setting with the spatial information from multiple thermal devices?*

In the next step, thermal feedback will be compared and used in combination with vibrotactile feedback, inspired by Section 2.2.5. The complexity of the cues will be increased, investigating cue designs with several factors and associations with temperatures, as discussed in Section 2.2.2, to convey more complex notifications (Section 2.4.2). First, notifications of different levels of urgency will be investigated, inspired by and adapted from [26, 18], where the different modalities encode the same information. In the next step, notifications with different levels of information will be compared, influenced by the use case of [44] and strengthened by mappings found in [112, 111]. Finally, the influence of bimodal tactile feedback in a multimodal environment was tested to inform on the transfer of control process, filling the gap identified in 2.4.3, taking inspiration for the location from [215] and mapping from [113].

Research Question 3: *How effectively can thermal feedback convey notifications in a car in a*
a. unimodal setting?
b. bimodal tactile setting?

This incremental introduction of thermal feedback into the driving environment will provide a solid basis for further investigation of thermal cues within the car. The next chapters will discuss the user experiments conducted to explore the novel application of thermal feedback in the vehicle.

Chapter 3

Thermal Binary Directional Cues

3.1 Introduction

Thermal feedback, as shown in the previous chapter, has been used in previous research to give directional cues. However, this was not in an automotive environment, where driving is a primary task demanding a high level of attention and identification of thermal directional cues becomes a secondary task. Therefore, experiments were designed and conducted to gain first insights into how thermal feedback influences driving and what kind of problems drivers face when identifying directional cues. Direct translation of thermal navigation as used in former research by, for example, Wettach *et al.* [40] or Tewell *et al.* [134], is not possible for the automotive sector, as their approach was reactive rather than anticipatory: when participants left the correct path the temperature would change. In cars, however, directional cues have to be given explicitly with ample time to make preparations for a safe turn or lane change to avoid dangerous incidents or crashes.

The first two studies presented in this chapter were conducted using a single device, comparable to former research, to investigate how binary instructions given by the direction of temperature change, i.e. warm or cold change, can be utilised in an automotive environment. This factor showed high recognition rates in previous research for mobile environments and was used to test the suitability of thermal feedback during driving. These experiments aim to answer Research Question 1:

How accurately can thermal feedback give binary direction cues in an automotive setting (with one thermal device)?

This chapter describes these first two experiments utilising a single device for binary feedback, starting with the description of the apparatus. A conclusion will discuss the findings in Section 3.6.

3.2 Apparatus

The hardware and setup used for these two first experiments were the same: participants were seated in an adjustable office chair facing an 23.6-inch HANNS-G HL249 screen. Attached to the table was a Logitech G920 Driving Force steering wheel, connected to a DELL XPS 15 9550 laptop using Windows 10. The thermal feedback was provided by a 2x2cm Peltier element, a thermoelectric device, which was mounted on a heat-sink, see Figure 3.1(a).

(a) Peltier element with heat-sink (b) Experimental Setup

Figure 3.1: Experiment 1 and 2: Hardware and experimental setup.

The control board setup was built by SAMH Engineering and details can be found in Appendix A.1.1. Communication with the control board was facilitated via Python 2.7. The device was placed on the tabletop on the right side of the participants, enabling them to touch the Peltier with the index finger of their right hand while driving one-handed with their left, see Figure 3.1(b). Throughout the experiment, participants wore Sennheiser HD 25-1 II Basic Edition headphones playing car noises during driving and audio instructions, if applicable. The audio instructions were created with the CereProc Cloud API[1]. The driving scenario was implemented in the Java-based OpenDS 3.5 free version[2] simulator, the communication with the Python-driven board was achieved via sockets. The driving environment depicted an empty five lane motorway, see Figure 3.2. The simulated car maintained a constant speed of 100km/h, participants were not provided with accelerator and brake pedals.

[1]https://www.cereproc.com/products/cloud, accessed 06/04/2020
[2]https://opends.dfki.de/, accessed 06/04/2020

Figure 3.2: Empty five lane motorway, implemented in OpenDS.

3.3 Experiment 1: Thermal Lane Change

This first experiment investigated if the presentation of thermal feedback during driving influenced driving performance and how well thermal directional instructions could be followed. The state-of-the-art non-visual feedback for navigation currently used in cars is speech. Therefore, the performance of thermal feedback was compared to this as a control condition.

3.3.1 Methodology

The study was designed as a within-subjects experiment with feedback type as the independent variable, where feedback type was either thermal or audio. The main goals of the experiment were to explore if the presentation of thermal feedback impacted driving performance and perceived workload. Furthermore, recognition rate, preferences regarding the two feedback types and time differences between them were investigated.

The experiment was split into two parts with both feedback types being presented in each 10 times. In the first part, participants kept in the middle lane and orally reported the identified cue to the experimenter, in the second part participants fulfilled lane changes according to the feedback they perceived. The feedback types themselves were not mixed, participants had distinctive driving blocks within each experimental part with only one feedback type, or condition, presented. The order of thermal and audio driving blocks in each part of the study was decided by iterating through all possible permutations, counterbalancing the conditions.

It was hypothesised that thermal feedback, as a novel tactile feedback, would be rated as more distracting than audio feedback and show more lane deviation and higher perceived workload. The thermal cues gradually increased, whereas speech feedback is abrupt in nature, so thermal feedback was expected to be rated as less disruptive and more pleasant. As a consequence, however, the time needed to complete a lane change would differ between the two conditions, with the gradual thermal feedback taking longer, as detection time would be increased. In addition, as previous literature has shown that there might be differences in perception between genders [52], results were compared between participating genders. Participants also were posed a question on thermal preferences regarding navigation, which was added as preparation for later study designs. Therefore, the hypotheses for this study were:

Hypothesis 1: Thermal feedback will lead to higher lane deviation and perceived workload than auditory cues;

Hypothesis 2: The time taken to complete a lane change will be longer in the thermal condition;

Hypothesis 3: Thermal feedback will be rated as less disruptive and more pleasant than the audio feedback;

Hypothesis 4: More participants will choose to turn towards the direction of the warm side of a thermal steering wheel.

The dependent variables evaluated for this experiment were: lane deviation, recognition rate, time to complete lane change, perceived workload and subjective ratings. Detailed descriptions of the dependent variables can be found in Section 3.3.4 *Measures*.

3.3.2 Driving Task and Feedback

The experiment was divided into two parts: in the first, participants should stay in the middle lane and report orally any feedback they received. This would ensure the best capturing of lane deviation to evaluate the distraction posed by the presentation of the feedback itself. In the second part, participants were asked to change lanes according to the feedback they identified. Participants were asked to drive one-handed with their left, placing their right index finger on the thermal device throughout driving, independent of condition.
10 invisible trigger elements were placed on the simulated road in regular intervals. After triggering one of these elements, the lane change instruction was presented within a random time interval between 0s and 4s. The direction of lane change was decided randomly, only restricted when the car was in one of the outer lanes and needed to change towards a specific direction to stay on the motorway.

The thermal feedback in both parts was identical and based on previous research [29, 268]: the Peltier devices were set to the neutral base temperature of 30°C at the beginning of the driving block. This fixed temperature, presented before and in between each cue, would

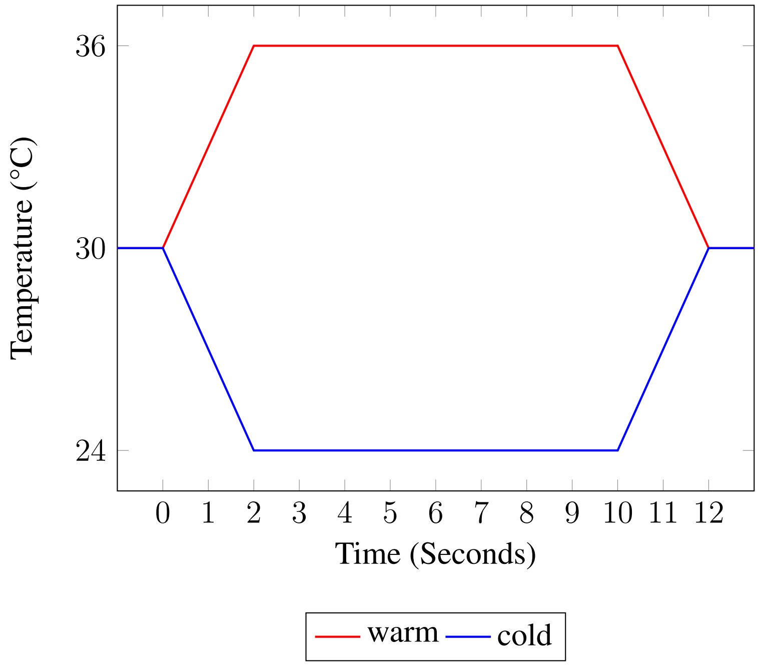


Figure 3.3: Experiment 1: Thermal feedback.

ensure that the skin in contact with the device adapted to the device temperature and led to controlled temperature changes on this location, independent of previous skin temperature. When a lane change to the right was requested, the thermal device would warm to 36°C with a rate of change of 3°C/s, resulting in 2s of temperature change (Figure 3.3 red line). This temperature was kept constant for 8s and was then returned to neutral at the same rate of change. The thermal feedback for leftward lane changes was identical in structure, but the temperature would decrease and cool to 24°C, see Figure 3.3 blue line. The complete stimulus, including the return to neutral, was introduced to participants as a single cue before their first thermal driving block.

In the audio condition, the voice feedback, uttered by a synthesised male voice, differed in the two parts. In the second part, where actual lane changes were required, the instructions were *right* and *left*. However, in comparison to the more abstract and novel thermal feedback the audio instructions were considered to potentially elicit a stronger response and unintended lane changes and, therefore, increase lane deviation in the first part. The speech instructions of the first part were *warm* and *cold*, respectively, to counteract this and to adapt it to the thermal feedback.

3.3.3 Participants and Procedure

The experiment was completed by fourteen participants, for details consult Table 3.1. All participants were right-handed, had at least corrected vision and reported no sensory impairments in their hands. In addition, they all held valid driving licenses: nine participants

	Number of Participants	Age (Years)	Driving Experience (Years)	Experience Simulator	Experience Audio	Experience Thermal
All	14	*R*: 20-34 *M* = 26.36; *SD* = 4.68	*R*: 1-17 *M* = 7.71 *SD* = 4.92	*R*: 1-5 *M* = 2.00 *SD* = 1.29	*R*: 1-5 *M* = 2.93 *SD* = 1.63	*R*: 1-3 *M* = 1.18 *SD* = 0.54
Female	8	*R*: 20-32 *M* = 24.75 *SD* = 4.77	*R*: 1-17 *M* = 6.88 *SD* = 6.03	*R*: 1-4 *M* = 1.75 *SD* = 1.16	*R*: 1-5 *M* = 2.75 *SD* = 0.75	*R*: 1 *M* = 1.00 *SD* = 0.00
Male	6	*R*: 23-34 *M* = 28.50 *SD* = 3.94	*R*: 5-14 *M* = 8.83 *SD* = 3.06	*R*: 1-5 *M* = 2.33 *SD* = 1.47	*R*: 1-5 *M* = 3.17 *SD* = 1.57	*R*: 1-3 *M* = 1.42 *SD* = 0.80

Table 3.1: Experiment 1: Detailed participant data, showing range (*R*), mean (*M*) and standard deviation (*SD*).

obtained them in countries with right-side driving, five in left-side driving countries.

Demographic data including gender, age, years of driving and were collected in addition to their experience with the technologies used (simulators, audio feedback and thermal feedback) prior to the experiment on a 5-point Likert scale (1 equalled none, 5 much). Participants reported their gender as either *female* or *male*, no participant chose the option *other*.

Recruitment of the participants was done via advertisement on university student pages and posters in the library, the School of Computing Science and the School of Psychology at the University of Glasgow. Participants were greeted in a usability testing room in the School Computing Science and presented with an information sheet. They signed a consent form and filled in the first questionnaire. Afterwards, participants were given time to get used to the driving simulator. They could drive on the empty five-lane motorway without any feedback present until they felt comfortable. Depending on the counterbalanced schedule, they then were introduced to their first feedback type, followed by the driving task for that condition. During driving, the feedback was presented 10 times, with the direction of lane change being random. After a short break the participants repeated this procedure for the second condition. At the introduction of the thermal feedback, it was made sure that participants could feel the feedback and identify the direction of the temperature change and also that they were familiar with the return to neutral.

In this first part, participants reported the identified feedback orally to the experimenter. After a short break, participants started the second part of the experiment, in which they were asked to turn one lane towards the direction indicated by the feedback, when prompted. Again, the counterbalanced schedule decided on the first condition.
In the break between the conditions of this second part, participants filled in the NASA TLX questionnaire and the additional scale for subjective ratings, capturing their impressions

of the just experienced feedback type. The same procedure was repeated for the second feedback type. At the end of the experiment, participants were presented with an additional questionnaire, capturing overall ratings and comments.

The documents used in the experiment, including information sheet, consent form and all questionnaires, can be found in Appendix A.2. The experiment design was approved by the Ethics Committee of the College of Science and Engineering of the University of Glasgow. The study was completed within one hour and each participant was paid £6.

3.3.4 Measures

The dependent variables were evaluated for all participants and then compared between the genders. One of the variables chosen to investigate the driver distraction was lane deviation: if drivers were distracted by the feedback identification, their driving performance would be less stable and lane deviation would increase. The driving logs generated by the driving simulator in the first part of the experiment provided the data for this. The deviation was calculated by comparing the Root Mean Square Error (RMSE) of the logged x-positions, with the value 0 describing the middle of the lane. A baseline lane deviation of 5s driving was taken before the onset of the stimulus and was then compared to time frames corresponding with the different levels of thermal changes: 2s of thermal change to 36°C or 24°C, 8s of constant temperature and 2s of returning to the neutral temperature of 30°C. This would allow a more detailed comparison of driving performance at different stages of the feedback.

Perceived workload was also captured as an indicator for distraction. The NASA TLX questionnaire [170] was utilised to collect perceived workload data. Participants rated the presented feedback on a 10-point Likert scale for the factors *Mental Demand*, *Physical Demand*, *Time Pressure*, *Effort*, *Performance*, *Frustration* and *Annoyance*. In addition, they were presented with a 5-point Likert scale, capturing subjective ratings on how *Pleasant*, *Comfortable*, *Disruptive* and *Complicated* the feedback felt to participants.

Furthermore, logging data from the second part of the experiment were utilised to calculate the time needed to complete a lane change. The time was taken from the onset of the stimulus triggering the lane change until the car had fully entered the lane. Recognition rates, i.e. correct lane changes, were also captured via logging data in the second part of the experiment. The oral reports of the first part were used to capture recognition there.

Participants were also asked to respond to the following question:
Imagine you were presented with thermal feedback on the steering wheel for navigation purposes, where the devices of one side of the wheel will be warmed, while the other side will be cooled, how would you interact:
If the right side of the steering wheel was warmed, while the left side was cooled, I would

turn to the: left/right
This question about participants' preference for the mapping of turning direction to direction of temperature change was posed to help design future experiments and confirm the mapping used in previous research [40, 134]. It was expected that participants would prefer to turn towards the warm side, as this was the mapping not only used in previous research, but also in children's games such as *Hot or Cold*. Participants also rated the different feedback types in the final questionnaire, asking *Please rate how much you liked the different instruction type* with an attached 5-point Likert scale, and asked to name reasons for their rating. In addition, they were asked to share ideas for applications using thermal feedback and locations where they thought it should be presented and were given ample space to comment on their experience. All questionnaire data (including NASA TLX) will be discussed in Section 3.3.5 *Results* under *Subjective Data*.

3.3.5 Results

All experiments in the thesis were newly evaluated using R[3]. This step was taken to ensure consistency and transparency throughout the thesis, as different types of software (SPSS[4], JASP[5] and R) were used during the course of the PhD, some of which were proprietary and/or the models used for evaluation were not reproducible. Results may therefore vary from results presented in the published papers. Substantial differences will be pointed out.

The comparisons were done with t-tests (*t(df)*), when the data were normally distributed, and Wilcoxon (V) tests otherwise. Shapiro Wilks tests were utilised throughout the thesis to determine normality. Paired versions of the tests were done between conditions, for all participants and for both gender groups individually, while unpaired tests were utilised for comparisons between the genders. For unpaired t-tests, R used Welch t-tests, for which the data was automatically adjusted for unequal variance between the two groups (adapted degree of freedom). Likert scale and NASA TLX data were compared with Wilcoxon tests. Participant comments throughout the thesis will be presented with typos removed and capitalisation adapted where needed.

Lane Deviation

The lane deviation of the four time frames *before* the stimulus, *during* the temperature change, during the *constant* temperature and at the *return* to neutral were compared with t-tests (*t(df)*) and Wilcoxon (V), for non-normally distributed data, between the feedback types

[3]https://www.r-project.org/
[4]https://www.ibm.com/products/spss-statistics
[5]https://jasp-stats.org/

	Before	During	Constant	Return
Condition All	$V = 29$ $p = 0.15$	$t(13) = 1.11$ $p = 0.29$	$t(13) = 1.39$ $p = 0.19$	$t(13) = 1.02$ $p = 0.33$
Condition Female	$t(7) = 0.66$ $p = 0.53$	$t(7) = 1.07$ $p = 0.32$	$t(7) = 1.82$ $p = 0.11$	$t(7) = 0.20$ $p = 0.85$
Condition Male	$t(5) = 1.58$ $p = 0.18$	$t(5) = 0.59$ $p = 0.58$	$t(5) = 1.03$ $p = 0.35$	$V = 4$ $p = 0.22$
Gender Thermal	$t(8.12) = 0.42$ $p = 0.69$	$t(9.19) = 0.19$ $p = 0.85$	$t(5.91) = 0.64$ $p = 0.55$	$t(7.72) = 0.73$ $p = 0.49$
Gender Audio	$t(9.73) = 0.31$ $p = 0.76$	$t(10.07) = 0.47$ $p = 0.65$	$t(6.84) = 0.01$ $p = 0.99$	$V = 21$ $p = 0.76$

Table 3.2: Experiment 1: Statistics for Comparison of Lane Deviation, captured during the first part of the experiment.

for all (*Condition All*) and each individual gender (*Condition Female / Condition Male*) and for each condition between the genders (*Gender Thermal / Gender Audio*). No significant differences were found, see Table 3.2.

Time to Complete Lane Change

The overall mean time to complete a lane change was 4.37s. In the thermal condition, the lane changes took significantly longer (M = 5.28s, SD = 0.75) than audio (M = 3.46s, SD = 0.42) ($t(13)$ = 12.82, $p < 0.001$). The lane change was 1.82s faster in the audio condition. Comparisons with t-tests of feedback type within genders showed significant results (female: $t(7) = 8.34$, $p < 0.001$; male: $t(5) = 11$, $p < 0.001$), where women changed 1.68s faster in the audio condition and men 2.02s, see Figure 3.4. The t-test comparison between the genders showed also a significant difference for both conditions (thermal: $t(11.02)$ = 5.9, p < 0.001; audio: $t(7.00)$ = 21.67, p < 0.001). In the thermal condition women changed 0.21s faster than men, while men changed 0.1s faster than women in the audio condition.

Recognition

Figure 3.5 shows all recognition rates. Recognition for audio feedback in both parts of the experiment was 100%: all speech stimuli were interpreted correctly. Thermal feedback had a recognition rate of 97% in the first part of the experiment. 4 out of 140 stimuli were erroneous: 3 stimuli were missed and one wrongly identified. Two of these (the wrong identification and one missed stimuli) occurred within the female, two within the male participants. This leads to a recognition rate of 98% for the female and 97% for the male participants. The difference in recognition between conditions was tested with Wilcoxon and not statistically significant (V = 6, p = 0.17) for the first part of the experiment, neither was the comparison

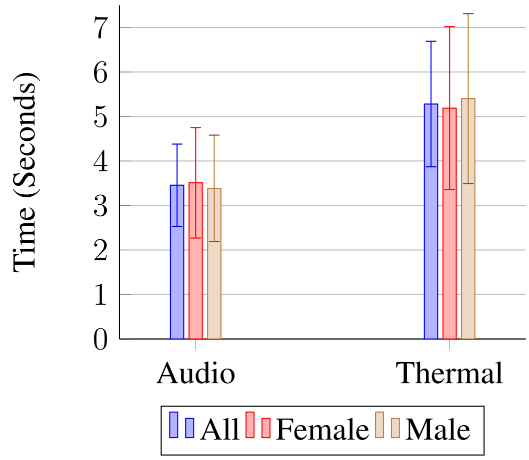


Figure 3.4: Experiment 1: Time to Complete Lane Change; error bars always show the standard error.

within (female: $V = 1$, $p = 1$; male: $V = 3$, $p = 0.35$) and between the genders ($V = 20$, $p = 0.53$). In addition to these identifications, 25 additional temperature changes were reported: 18 by women and 7 by men. These occurred as a result of misinterpreting the return to neutral as a new stimulus, a false positive. The difference in gender for this was not statistically significant ($V = 29$, $p = 0.54$).
While all speech stimuli were recognised correctly again with lane changing in the second part of the experiment, 16 thermal stimuli were missed (12 by women and 4 by men), resulting in a recognition rate of 88% overall, 85% for women and 93% for men. This difference was tested with Wilcoxon and statistically significant ($V = 36$, $p = 0.01$) for conditions for participants, but the comparisons within (female: $V = 15$, $p = 0.06$; male: $V = 6$, $p = 0.17$) and between genders ($V = 29.5$, $p = 0.49$) were not significant. The number of false positives went down to 8: 6 occurred when temperatures were returning to neutral from cold stimuli and 2 from warm. All these false positives were identified by female participants.

Subjective Data

The perceived workload was collected with NASA TLX questionnaires, see Figure 3.6, and evaluated with Wilcoxon tests. Overall workload showed significant differences ($V = 11$, $p = 0.007$). Detailed results of the comparisons can be seen in Table 3.3. Mental Demand (median(audio) = 3.00, median(thermal) = 7.00) showed statistically significant results between the two conditions thermal and audio for all participants, as did Performance (median(audio) = 8.00, median(thermal) = 5.00) and Frustration (median(audio) = 1.25, median(thermal) = 3.75). None of these categories was significantly different within the gender groups and between genders. The only statistically different results in the comparison between genders was found for Physical Demand for thermal feedback: the male participants rated thermal feedback significantly more physically demanding than female participants (median(female)

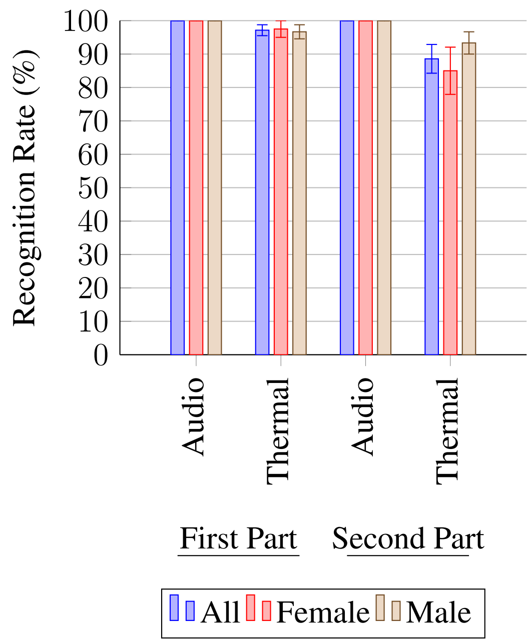


Figure 3.5: Experiment 1: Recognition Rate; significant results are in bold font.

= 2.25, median(male) = 4.75).

	Mental Demand	Physical Demand	Time Effort	Effort	Perfor-mance	Frustra-tion	Annoy-ance
Condition All	$V = 4.5$ **$p = 0.007$***	$V = 33.5$ $p = 0.69$	$V = 34$ $p = 0.94$	$V = 20.5$ $p = 0.16$	$V = 8.5$ **$p = 0.02$***	$V = 7.5$ **$p = 0.03$***	$V = 9.5$ $p = 0.14$
Condition Female	$V = 3$ $p = 0.08$	$V = 25.5$ $p = 0.32$	$V = 6.5$ $p = 0.46$	$V = 11$ $p = 0.67$	$V = 6$ $p = 0.20$	$V = 4$ $p = 0.11$	$V = 2$ $p = 0.17$
Condition Male	$V = 0$ $p = 0.06$	$V = 0$ $p = 0.10$	$V = 10.5$ $p = 0.50$	$V = 1$ $p = 0.10$	$V = 0$ $p = 0.06$	$V = 1$ $p = 0.20$	$V = 3$ $p = 0.58$
Gender Thermal	$V = 18$ $p = 0.47$	$V = 40$ **$p = 0.04$***	$V = 14.5$ $p = 0.24$	$V = 27.5$ $p = 0.70$	$V = 30.5$ $p = 0.44$	$V = 24.5$ $p = 1.00$	$V = 18$ $p = 0.47$
Gender Audio	$V = 24$ $p = 1.00$	$V = 21$ $p = 0.75$	$V = 27.5$ $p = 0.69$	$V = 31$ $p = 0.40$	$V = 27$ $p = 0.7$	$V = 19.5$ $p = 0.60$	$V = 26.5$ $p = 0.79$

Table 3.3: Experiment 1: Statistics for NASA TLX rating of workload; significant results are bold and marked with an asterisk.

The additional subjective ratings were collected on a 5-point Likert scale and the results can be seen in Figure 3.4. Results of the statistical analysis with Wilcoxon tests can be found in Table 3.4. Only the factor Complicated was found to be statistically significant for all participants as well as within both gender groups (all: median(audio) = 1, median(thermal) = 3.00; female: median(audio) = 1.25, median(thermal) = 2.25; male: median(audio) = 1.00, median(thermal) = 3.50). In the comparison between genders, Disruptive was found to be significantly different, where male participants rated audio to be more disruptive than female participants (median(female) = 1.00, median(male) = 2.25).

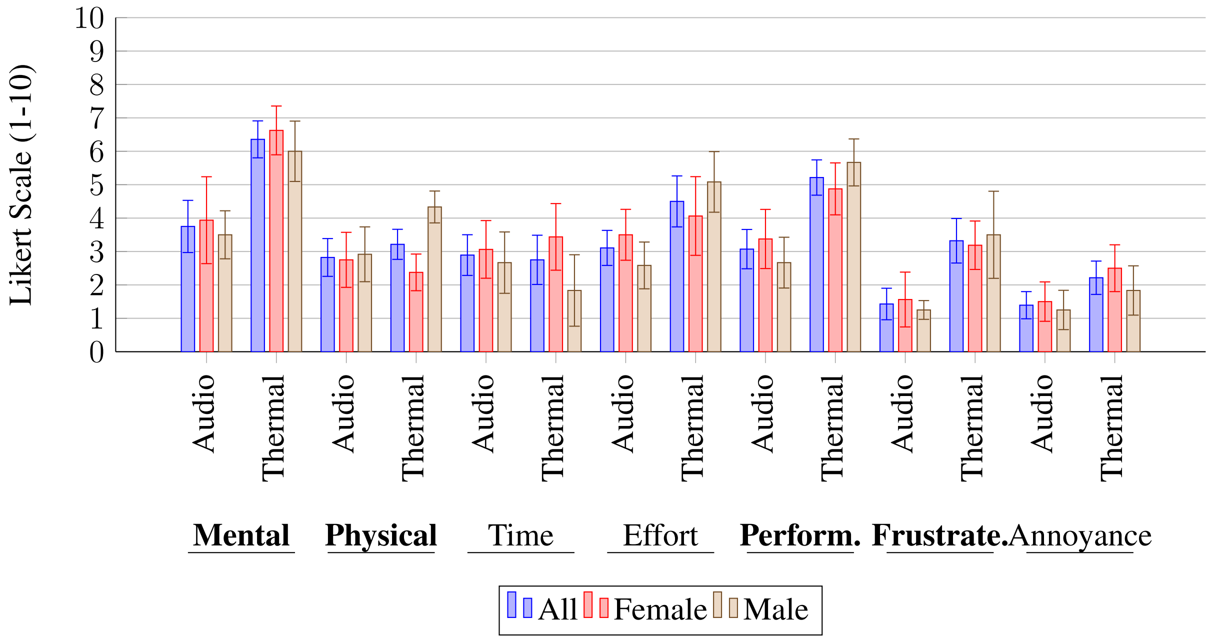


Figure 3.6: Experiment 1: Perceived workload; significant results are in bold font.

The final rating at the end of the experiment, see Figure 3.8, showed no significant difference between conditions for all participants ($V = 73$, $p = 0.54$) and within gender (female: $V = 22.5$, $p = 0.17$; male: $V = 17$, $p = 0.20$), as well as between genders ($V = 20$, $p = 0.64$).

When asked for reasons of their rating, participants mentioned that thermal required more concentration. *P03*, for example, stated they had *to concentrate a lot more for thermal - difficult to judge if it had gone hot/cold whereas audio was much clearer* and *P02* wrote that they *found the thermal instructions more difficult to follow, requiring much more concentration. Sometimes it was hard to distinguish if the temperature was going back to neutral or was getting warm. On the other hand, audio instructions were clear to understand*. Problems with distinguishing between the return to neutral and new stimuli were also reported by *P08*: *Thermal instructions are unclear - not sure it an actual instruction, or just returning to 30 degree* and *P09* agreed: *Thermal was tricky sometimes because I wasn't sure when the temperature had gone back to neutral*. Participants also commented on uncertainty in the thermal condition that they did not experience in the audio condition: *At times I wasn't so sure about the temperature. Basically, didn't trust my sense of touch* (*P06*) and *the audio made me nervous, but I clearly new were I was supposed to go. Because the thermal stimuli was similar to me I was not sure when I was supposed to turn although I was less nervous* (*P05*). The more disruptive nature of the audio feedback described here by *P09* was affirmed by other participants, who wrote *audio can be a bit annoying and demands some concentration while thermal cannot interfere with other senses or activity* (*P01*). The speech feedback was familiar to participants, as *P10* mentioned that it *was easier to follow the audio instructions, possibly because I am used to driving with GPS*. *P14* wrote that audio was *like*

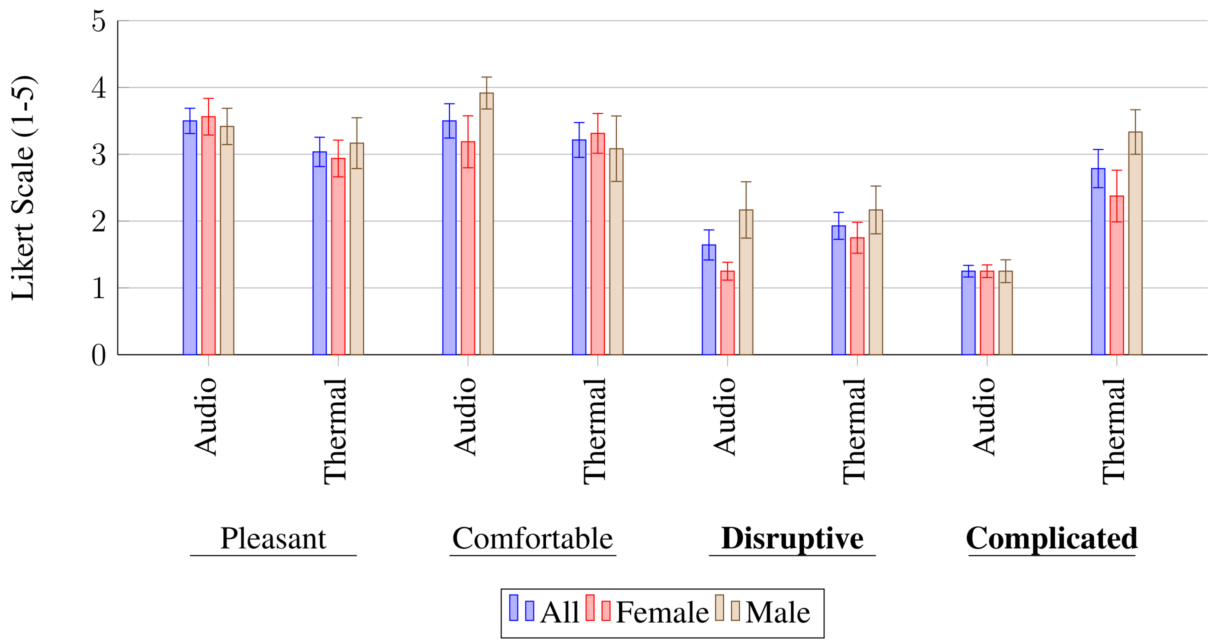


Figure 3.7: Experiment 1: Subjective Additional Ratings; significant results are in bold font.

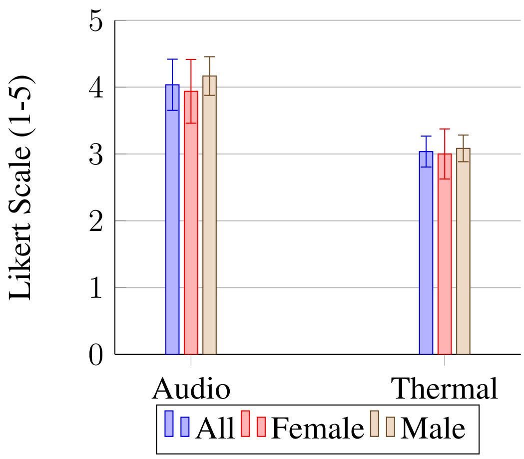


Figure 3.8: Experiment 1: Final rating for both feedback types.

listening to a sat nav and *P12* commented that they *found the thermal type distracts from my focusing on driving. Maybe because I was not familiar with it*.

When answering the question about preferred turning direction, most participants answered *Right*, favouring the mapping of warm temperature changes to direction of turn. Only one participant chose *Left*.

Participants had several suggestions for the use of thermal feedback in the car. *P02* suggested using thermal interaction to give feedback on distances, for example when parking, which was also mentioned by *P07*. *P03* suggested that warming the steering wheel when speeding might be useful. *P14* had several ideas: *How far away you were from hazards - plan routes, avoid traffic, outside weather conditions*. Hazard warnings were also mentioned by *P11*,

	Complicated	Pleasant	Disruptive	Comfortable
Condition All	$V = 0$ $\boldsymbol{p = 0.002}$*	$V = 52$ $p = 0.09$	$V = 17$ $p = 0.16$	$V = 30.5$ $p = 0.37$
Condition Female	$V = 0$ $\boldsymbol{p = 0.04}$*	$V = 23.5$ $p = 0.12$	$V = 2$ $p = 0.09$	$V = 6$ $p = 0.78$
Condition Male	$V = 0$ $\boldsymbol{p = 0.04}$*	$V = 7$ $p = 0.58$	$V = 6.5$ $p = 0.90$	$V = 9$ $p = 0.20$
Gender Thermal	$V = 36.5$ $p = 0.11$	$V = 27.5$ $p = 0.67$	$V = 31.5$ $p = 0.36$	$V = 21$ $p = 0.74$
Gender Audio	$V = 26$ $p = 0.83$	$V = 27.5$ $p = 0.67$	$V = 5.8$ $\boldsymbol{p = 0.04}$*	$V = 13.5$ $p = 0.19$

Table 3.4: Experiment 1: Statistics for Subjective Additional Ratings; significant results are bold and marked with an asterisk.

P10 and *P05*, whereas *P09* would also see use in providing information regarding weather conditions. *P11* would like to be reminded to turn on the lights, while *P13* would prefer thermal feedback on the gear stick to indicate they should change gears.

Overall, 5 participants could imagine thermal feedback being presented on the gear stick. However, the steering wheel was the most popular location (9 participants). In addition, 4 participants named the seat, and one participant each the seat belt, gear pedals and door handle.

3.3.6 Experiment 1 Discussion

This first experiment compared thermal and speech feedback for lane change instructions to gain some first insights into the suitability of thermal feedback during driving. The sample size in the experiment (and all others discussed in this thesis) was comparably small, a higher and more diverse number of participants could make the results more robust and might show different results. However, the experiments in this thesis present interesting first insights into the basics of thermal feedback within the car environment. More discussion on limitations of the studies can be found in Section 6.5 *Limitations and Future Work*.

Temperature changes for in-car interaction, opposite to speech feedback, was a novel concept and needed additional mapping. Therefore, it was hypothesised that thermal feedback would show an increased level of distraction from the primary task of driving, which would influence the driving performance and show differences in lane deviation as well as perceived workload. However, the lane deviation showed no statistically significant differences between the conditions for any of the observed time frames. No definite conclusion could therefore be drawn. However, participants commented on having to concentrate more to follow the thermal instructions, which could have a greater impact on driving in more complex driving scenarios. Perceived workload showed differences in mental demand, performance and frustration. Thermal feedback was rated worse than speech in all these categories, indicating higher workload. *Hypothesis 1* could, therefore, be partly corroborated.

Lane changes took an average of 1.82s longer in the thermal condition than in the audio condition, as claimed in *Hypothesis 2*. The difference for the female participants was statistically significantly smaller than for the male participants, with 1.68s and 2.02s, respectively. The gender differences within the conditions were also different: men were faster than women in the audio and women faster than men in the thermal condition.

The recognition rates did not significantly differ between the genders. However, the faster lane change times of the female participants could indicate a faster detection of temperature changes. Furthermore, male participants rated thermal feedback as more physically demanding, which adds to the impression that women could be more sensitive to thermal feedback than men. Interestingly, only the male participants rated audio feedback as more disruptive than thermal feedback, seemingly showing more sensitivity towards audio feedback than female participants.

Hypothesis 3 expected thermal feedback to be rated as less disruptive and more pleasant than speech. However, there were no significant differences found for pleasantness ratings. Some participants commented on how the audio feedback made them nervous or could be annoying. However, only the comparisons between genders found differences for disruptiveness: men rated audio feedback as more disruptive then women, but not more than thermal feedback.

Participants of both genders agreed on thermal feedback being more complicated than audio feedback. One of the reasons for this was the additional mapping needed to translate temperature change to lane change direction. Familiarity with speech navigation systems was named as another one. However, the most prominent reason seems to be uncertainty connected to thermal feedback, but not speech navigation. The return to the base temperature needed between thermal cues was confusing to participants and resulted in additional 25 reported temperature changes in the first and 8 additional lane changes in the second part of the study. The cues had the same rate of change for the temperature changes towards the goal temperature and when returning to the base temperature, which made the return feel the same as a new stimulus in the opposite direction of change. A less symmetrical design could help minimise the number of false positives. In addition to this, some thermal cues were also missed in both parts of the study, while audio feedback had perfect recognition rate, indicating the need to further improve the cue design.

At the end of the experiment, a question regarding the preferred mapping of direction of temperature change to turning direction was posed. *Hypothesis 4* claimed that more participants would choose to turn towards the warm side, and all but one participant confirmed this mapping.

The results of this first study clearly show that thermal feedback has potential for in-car use, with recognition rates of 97% in the first and 88% in the second part. However, the return to the neutral temperature was identified as a source of confusion and misinterpretation. A second experiment was therefore devised, aiming to explore different aspects of thermal cue design in order to minimise the number of false positives and maximise the recognition rate.

3.4 Experiment 2: Different Stimuli Designs

In this experiment, several design factors for thermal feedback were explored to investigate their influence on recognition rate and number of false positives. In addition to direction of temperature change, three other factors where tested: length of temperature presentation, extent of temperature change and rate of temperature change at the return to the neutral temperature.

3.4.1 Methodology

The study was designed as a within-subjects experiment with the four independent variables direction (*DIR*), extent (*EXT*), length (*LEN*) and rate (*ROC*) of temperature change.

The rate of temperature change was expected to have an influence on the number of false positive recognitions: the slower the temperature would return to neutral, the less conspicuous the change would be and the less it would be interpreted as a new stimulus. In addition, it was hypothesised that a shorter presentation of the temperature would lead to less false positives, as the skin had less time to adapt to the presented temperature and would therefore be less sensitive to the change back. The recognition rate was expected to be mostly influenced by the extent of temperature change: the bigger the change in temperature, the better it should be recognised. The hypotheses for this experiment, therefore, were defined as:

Hypothesis 1: The slowest return to the neutral temperature will have the smaller number of false positive lane changes at the return to the neutral temperature;

Hypothesis 2: A shorter presentation time will have the smallest number of false positive lane changes at the return to the neutral temperature;

Hypothesis 3: The higher extent of temperature change will have the better recognition rate.

Dependent variables were: recognition rate, number of false positives and time to complete lane change. As in the first experiment, the results were analysed for the two genders male and female. More information on the dependent variables can be found in Section 3.4.4 *Measures*.

3.4.2 Driving Task and Feedback

The driving scenario was similar to the first experiment. Participants again drove on a five-lane motorway and asked to change lanes depending on the temperature change they felt: warm thermal cues directed towards the next rightward lane, cold temperature changes towards the next leftward lane.

The factors for the thermal feedback were:

- *DIR*: direction of temperature change, either warm or cold
- *LEN*: length of temperature presentation, either 0s, 3s, or 6s
- *EXT*: extent of temperature change, either 3°C or 6°C
- *ROC*: rate of temperature change, either 1°C/s (slow) or simulated 0.5°C/s (angled).

Figure 3.9 visualises all combinations of these factors. Because of limitations of the hardware, which only enabled rate of changes of either 1°C/s or 3°C/s, any rate slower than this had to be simulated. The angled rate of change of 0.5°C/s was achieved by changing 1°C with a rate of change of 1°C/s and then keeping this temperature for 1s. This procedure was repeated until the neutral temperature was reached, see dashed lines in Figure 3.9.

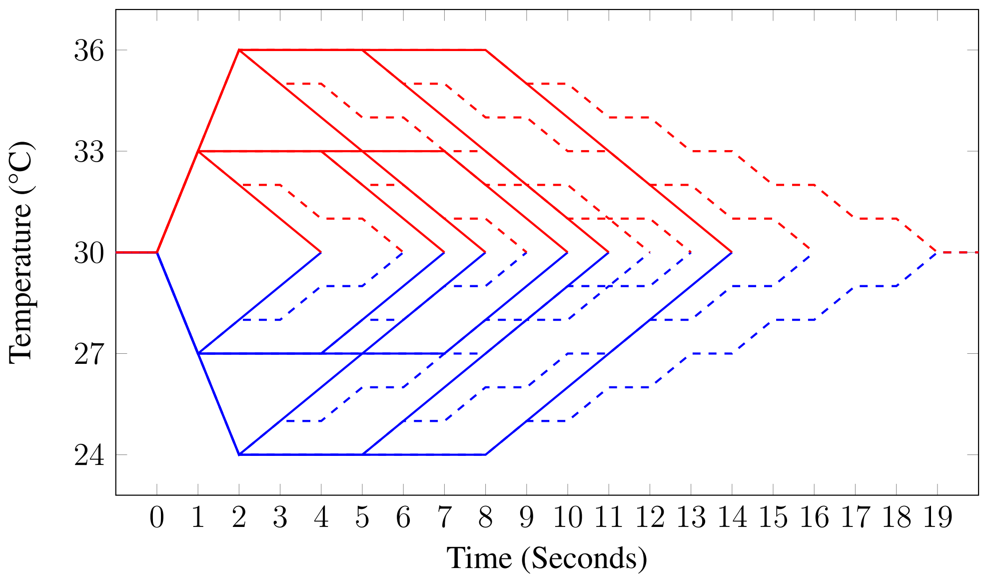


Figure 3.9: Experiment 2: Thermal feedback.

A labelling system was introduced with describing DIR-LEN-EXT-ROC. A cold temperature change of 3°C, lasting 3s and returning to neutral with an angled rate of change would be labelled *c-3-3-a*. Every combination was presented to participants three times, resulting in 72 cues in total. The order of the stimuli was randomised.

	Number of Participants	Age (Years)	Driving Experience (Years)	Experience Simulator	Experience Thermal
All	16	*R*: 19-35 *M* = 25.88; *SD* = 5.06	*R*: 0-17 *M* = 5.28 *SD* = 5.20	*R*: 1-5 *M* = 3.25 *SD* = 1.29	*R*: 1-4 *M* = 2.00 *SD* = 1.32
Female	8	*R*: 19-35 *M* = 24.75 *SD* = 5.63	*R*: 1-17 *M* = 6.13 *SD* = 6.17	*R*: 1-5 *M* = 3.00 *SD* = 1.31	*R*: 1-4 *M* = 2.00 *SD* = 1.31
Male	8	*R*: 21-35 *M* = 27.00 *SD* = 4.50	*R*: 0-14 *M* = 4.44 *SD* = 4.27	*R*: 1-5 *M* = 3.55 *SD* = 1.31	*R*: 1-4 *M* = 2.00 *SD* = 1.41

Table 3.5: Experiment 2: Detailed participant data, showing range (*R*), mean (*M*) and standard deviation (*SD*).

3.4.3 Participants and Procedure

Sixteen newly recruited participants, eight female and eight male, completed the experiment. Their age range, driving experience and prior experience with driving simulators and thermal feedback (on 5- point Likert scale with 1 being no experience) are presented in Table 3.5. All participants held valid driving licenses and at least corrected vision. They reported no sensory impairments and were right-handed. Eleven participants obtained their driving licenses in countries with right-side driving.

Recruitment was done through mailing lists and university web pages. The study was conducted in the School of Computing Science at the University of Glasgow. Participants were greeted and presented with the information sheet. After thoroughly reading through it, they signed the consent form. Participants were given some time to get used to the driving simulator, driving on the empty motorway until they felt comfortable. This took approximately between 1min and 3min. Afterwards, the different stimuli were introduced in detail. The driving task itself was divided into 8 blocks with 9 randomly chosen stimuli each, lasting about 5min and divided by short breaks. At the end of the experiment participants filled in a questionnaire collecting demographic data. The questionnaire, as well as the information sheet and consent form can be found in Appendix A.3. The experiment took approximately an hour and participants were paid £6.

3.4.4 Measures

The dependent variables investigated in this study were extracted from the logging files of the driving simulator and calculated similarly to the first study. Recognition rates and the number of false positives were the main interest. In addition, the time to complete lane change was calculated, as affirmation of the value found in the first experiment. The results were again evaluated for all participants and the two represented genders.

3.4.5 Results

Thermal perception of warm and cold temperatures varies, so the data were evaluated separately for warm and cold stimuli with repeated measures analysis of variance (ANOVA), testing for variables LEN, EXT and ROC. For comparison of gender differences, Gender was added as between subject factor. *Post hoc* tests were conducted with Tukey adjustments, automatically provided by R, to adjust for multiple comparisons. Outliers varying more than two standard deviations from the mean were removed before evaluation. There was only one outlier for Time to Complete Lane Change.

Recognition

Recognition rates for all cold and warm stimuli can be seen in Figures 3.10 and 3.11, respectively. Only one stimulus (DIR-LEN-EXT-ROC), *w-6-6-a*, had a recognition of 100% overall. Six more stimuli were also always recognised correctly by female participants (see Figures 3.10 and 3.11), but not by male participants. The worst recognition rate was found for *w-0-3-s* with 58%. All other stimuli had recognition rates over 70%.
Statistical evaluation with repeated measures ANOVA for all participants (see Table 3.6) showed significant results for cold stimuli only for the variable EXT, while recognition of warm stimuli was influenced by both LEN and EXT and also showed significant differences for the interaction between LEN and EXT. Significant gender differences were not found (see Table 3.7). Higher temperature changes led to a better recognition for both warm ($t(15)$ = 4.81, p = 0.0002) and cold ($t(15)$ = 2.89, p = 0.01) stimuli. *Post hoc* tests with Tukey adjustments for LEN of warm stimuli showed significant differences for 0 - 3 ($t(30)$ = 4.32, p = 0.0005) and 0 - 6: $t(30)$ = 3.63, p = 0.003), but not 3 - 6 ($t(30)$ = 0.69, p = 0.77). Stimuli with LEN of 0 had lower recognition rates.
Post hoc test statistics with Tukey adjustments for the interaction between LEN and EXT for warm stimuli can be found in Table 3.8. The combination 0,3 was significantly worse recognised than all other combinations.

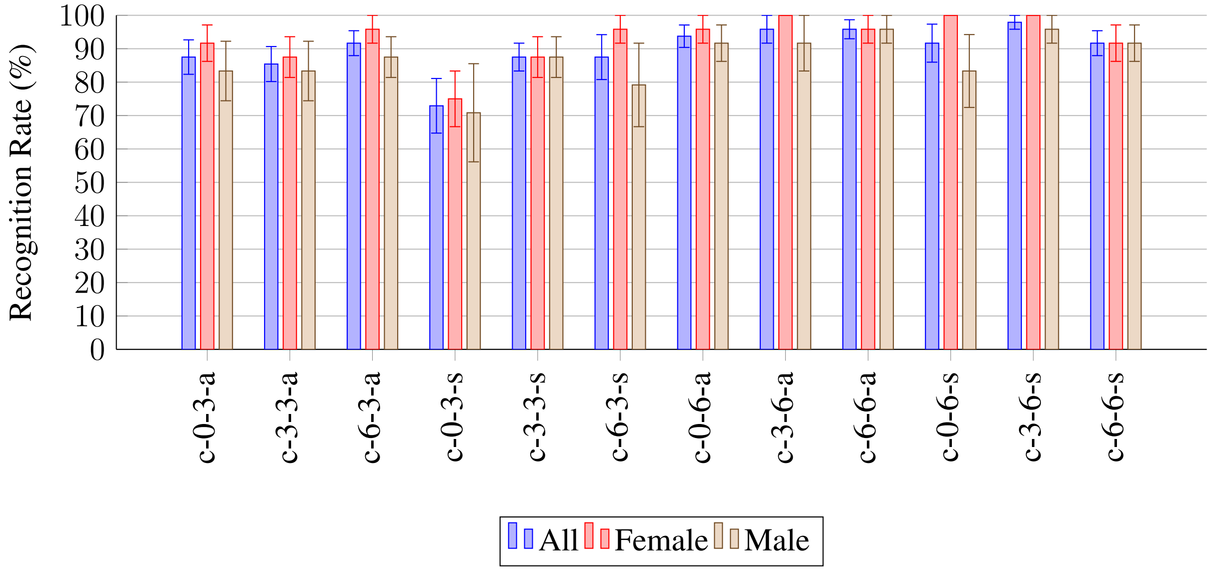


Figure 3.10: Experiment 2: Recognition Rate for all Cold Stimuli.

	LEN	EXT	ROC	LEN: EXT	LEN: ROC	EXT: ROC	LEN: EXT: ROC
Cold All	*F(2,30)* = 1.34 *p* = 0.28	*F(1,15)* = 8.37 ***p* = 0.01***	*F(1,15)* = 1.47 *p* = 0.24	*F(2,30)* = 1.33 *p* = 0.28	*F(2,30)* = 1.34 *p* = 0.28	*F(1,15)* = 0.85 *p* = 0.37	*F(2,30)* = 1.22 *p* = 0.31
Warm All	*F(2,30)* = 10.75 ***p* < 0.001***	*F(1,15)* = 23.13 ***p* < 0.001***	*F(1,15)* = 2.36 *p* = 0.15	*F(2,30)* = 7.33 ***p* = 0.003***	*F(2,30)* = 1.12 *p* = 0.34	*F(1,15)* = 0.60 *p* = 0.45	*F(2,30)* = 1.54 *p* = 0.23

Table 3.6: Experiment 2: Statistics for Recognition Rates for all participants; significant results are bold and marked with an asterisk.

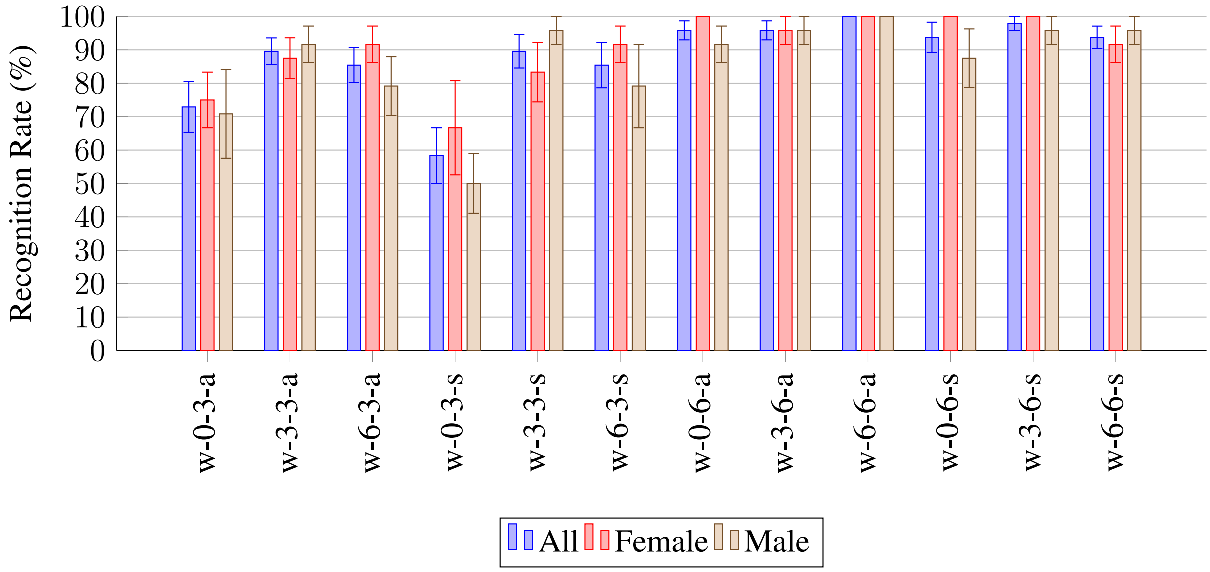


Figure 3.11: Experiment 2: Recognition Rate for all Warm Stimuli.

	Gender: LEN	Gender: EXT	Gender: ROC	Gender: LEN: EXT	Gender: LEN: ROC	Gender: EXT: ROC	Gender: LEN: EXT: ROC
Cold	*F(2,28)* = 0.15 *p* = 0.86	*F(1,14)* = 0.05 *p* = 0.83	*F(1,14)* = 0.06 *p* = 0.82	*F(2,28)* = 1.71 *p* = 0.20	*F(2,28)* = 0.27 *p* = 0.77	*F(1,14)* = 0.09 *p* = 0.77	*F(2,28)* = 0.94 *p* = 0.40
Warm	*F(2,28)* = 2.89 *p* = 0.07	*F(1,14)* = 0.04 *p* = 0.84	*F(1,14)* = 0.09 *p* = 0.77	*F(2,28)* = 2.33 *p* = 0.16	*F(2,28)* = 0.44 *p* = 0.65	*F(1,14)* = 0.00 *p* = 1.00	*F(2,28)* = 0.51 *p* = 0.61

Table 3.7: Experiment 2: Statistics for Recognition Rates with Gender as between subject factor; significant results are bold and marked with an asterisk.

LEN,EXT	*t*	*p*
0,3 - 3,3	*t(60.0)* = 5.60	< **0.0001***
0,3 - 6,3	*t(60.0)* = 4.63	**0.0003***
0,3 - 0,6	*t(41.4)* = 6.04	< **0.0001***
0,3 - 3,6	*t(48.1)* = 6.49	< **0.0001***
0,3 - 6,6	*t(48.1)* = 6.49	< **0.0001***
3,3 - 6,3	*t(60.0)* = 0.97	0.92
3,3 - 0,6	*t(48.1)* = 1.08	0.89
3,3 - 3,6	*t(41.4)* = 1.51	0.66
3,3 - 6,6	*t(48.1)* = 1.51	0.66
6,3 - 0,6	*t(48.1)* = 1.95	0.39
6,3 - 3,6	*t(48.1)* = 2.38	0.18
6,3 - 6,6	*t(41.4)* = 2.37	0.19
0,6 - 3,6	*t(60.0)* = 0.49	1.00
0,6 - 6,6	*t(60.0)* = 0.49	1.00
3,6 - 6,6	*t(60.0)* = 0.00	1.00

Table 3.8: Experiment 2: Statistics for Recognition Rate *post hoc* tests for the Interaction between LEN and EXT for warm stimuli of all participants; significant results are bold and marked with an asterisk.

Number of False Positive Lane Changes

Figures 3.12 and 3.13 show rates for all false positives for cold and warm temperature changes, respectively. The highest numbers of false positives can be found for stimuli *c-6-6-a* and *w-6-6-s* with 17%. The lowest rate was 2%, which was presented for *c-0-6-s* and *w-0-6-s*. Statistical evaluations with repeated measures ANOVA for all participants (see Table 3.9) and gender influences (see Table 3.10) revealed no significant effects.

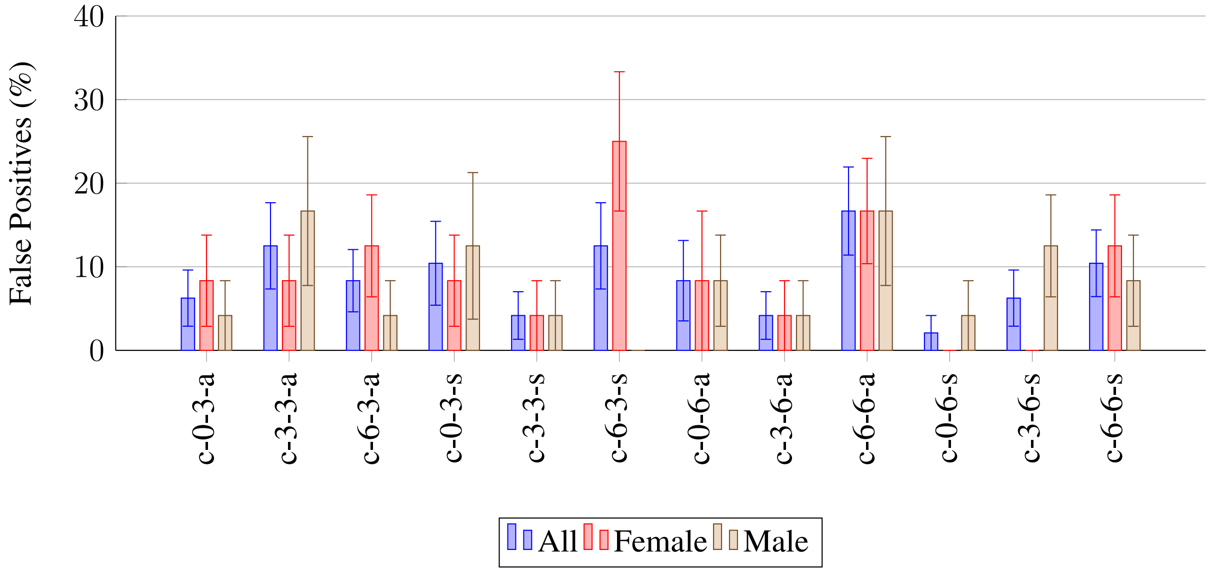


Figure 3.12: Experiment 2: False Positives for all Cold Stimuli.

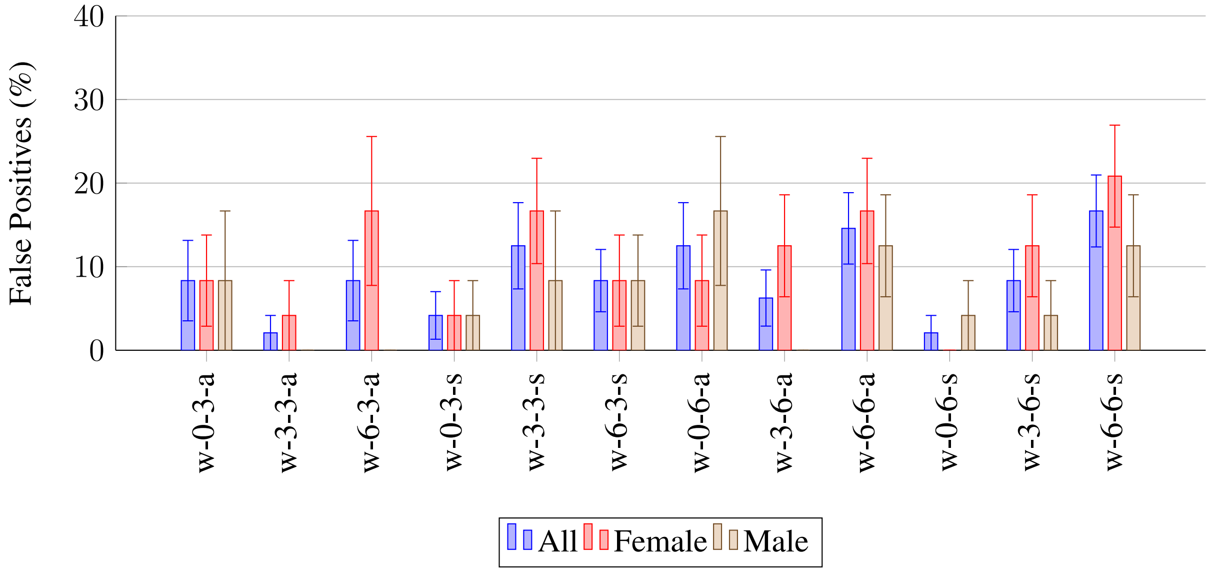


Figure 3.13: Experiment 2: False Positives for all Warm Stimuli.

	LEN	EXT	ROC	LEN: EXT	LEN: ROC	EXT: ROC	LEN: EXT: ROC
Cold All	*F(2,30)* = 1.92 p = 0.16	*F(1,15)* = 0.35 p = 0.57	*F(1,15)* = 0.39 p = 0.54	*F(2,30)* = 0.64 p = 0.53	*F(2,30)* = 0.10 p = 0.90	*F(1,15)* = 0.39 p = 0.54	*F(2,30)* = 3.05 p = 0.06
Warm All	*F(2,30)* = 2.42 p = 0.11	*F(1,15)* = 1.20 p = 0.29	*F(1,15)* = 0.00 p = 1.00	*F(2,30)* = 0.74 p = 0.49	*F(2,30)* = 3.11 p = 0.06	*F(1,15)* = 0.77 p = 0.39	*F(2,30)* = 0.66 p = 0.52

Table 3.9: Experiment 2: Statistics for False Positives for all participants; significant results are bold and marked with an asterisk.

	Gender: LEN	Gender: EXT	Gender: ROC	Gender: LEN: EXT	Gender: LEN: ROC	Gender: EXT: ROC	Gender: LEN: EXT: ROC
Cold	*F(2,28)* = 2.79 p = 0.08	*F(1,14)* = 3.35 p = 0.09	*F(1,14)* = 0.04 p = 0.85	*F(2,28)* = 0.81 p = 0.46	*F(2,28)* = 1.36 p = 0.27	*F(1,14)* = 0.64 p = 0.44	*F(2,28* = 1.25 p = 0.30
Warm	*F(2,28)* = 3.06 p = 0.06	*F(1,14)* = 0.16 p = 0.69	*F(1,14)* = 0.26 p = 0.62	*F(2,28)* = 0.36 p = 0.70	*F(2,28)* = 0.44 p = 0.65	*F(1,14)* = 0.47 p = 0.50	*F(2,28* = 0.98 p = 0.39

Table 3.10: Experiment 2: Statistics for False Positives with Gender as between subject factor; significant results are bold and marked with an asterisk.

Time to Complete Lane Change

Results of one male participant had to be removed, as the data differed more than two standard deviations from the mean. The Time to Complete Lane Change for all cold and warm stimuli can be seen in Figure 3.14 and 3.15, respectively. Stimulus *c-6-3-a* led, on average, to the fastest lane change (4.20s), while both *w-3-6-s* and *w-6-6-s* took the longest (4.97s).

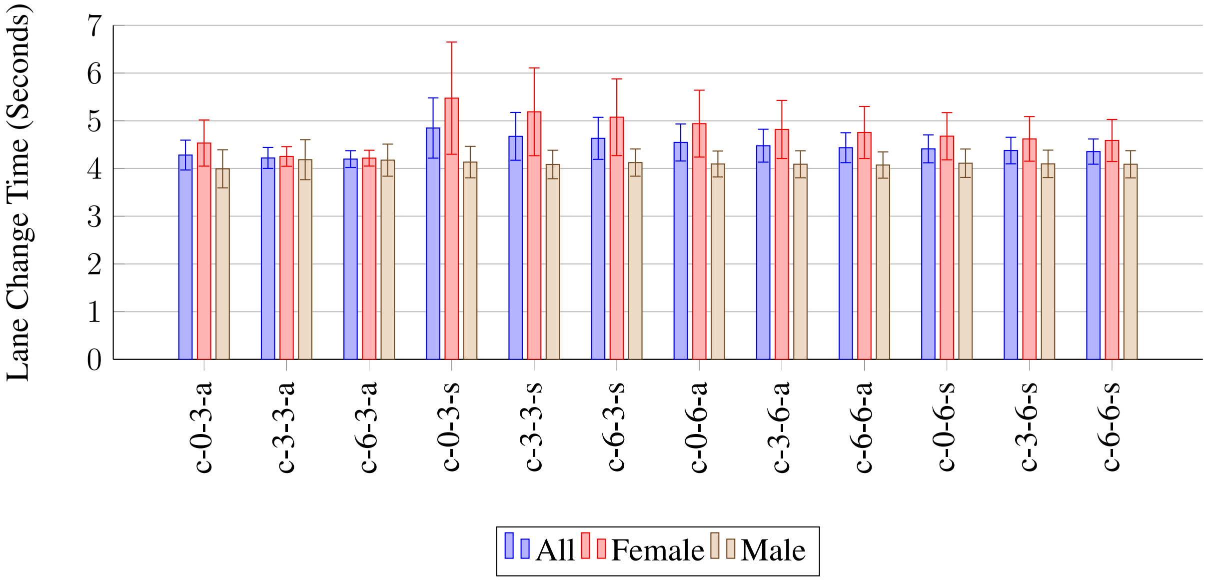


Figure 3.14: Experiment 2: Time to Complete Lane Change for all Cold Stimuli.

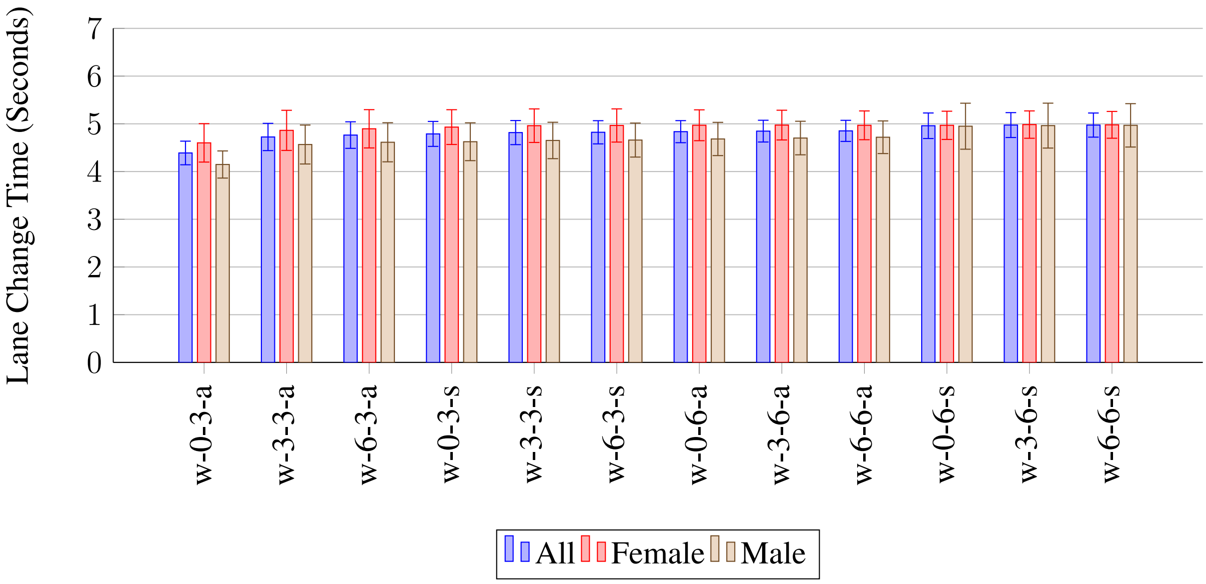


Figure 3.15: Experiment 2: Time to Complete Lane Change for all Warm Stimuli.

When evaluating the times for all participants with repeated measures ANOVA (see Table 3.11), no significant influence of the variables was found for cold stimuli, whereas LEN and EXT influenced the time for warm stimuli. *Post hoc* tests with Tukey adjustments for

LEN showed significant differences for 0 - 6 (*t(28)* = 2.75, *p* = 0.03), where the longer stimulus presentation led to longer lane change times, but not 0 - 3 (*t(28)* = 2.43, *p* = 0.05) or 3 - 6 (*t(28)* = 0.32, *p* = 0.95). *Post hoc* tests with Tukey adjustments for EXT showed that the larger extent of temperature change led to longer lane change times (*t(14)* = 2.41, *p* = 0.03). The evaluation of gender differences for Time to Complete Lane Change showed no significant results, see Table 3.12.

	LEN	EXT	ROC	LEN: EXT	LEN: ROC	EXT: ROC	LEN: EXT: ROC
Cold All	*F(2,28)* = 1.27 *p* = 0.30	*F(1,14)* = 0.16 *p* = 0.69	*F(1,14)* = 0.72 *p* = 0.41	*F(2,28)* = 0.33 *p* = 0.72	*F(2,28)* = 0.12 *p* = 0.89	*F(1,14)* = 0.94 *p* = 0.35	*F(2,28)* = 0.32 *p* = 0.73
Warm All	*F(2,28)* = 4.53 ***p* = 0.02***	*F(1,14)* = 5.83 ***p* = 0.03***	*F(1,14)* = 4.52 *p* = 0.05	*F(2,28)* = 2.82 *p* = 0.08	*F(2,28)* = 2.14 *p* = 0.14	*F(1,14)* = 0.60 *p* = 0.45	*F(2,28)* = 2.35 *p* = 0.11

Table 3.11: Experiment 2: Statistics for Time to Complete Lane Change for all participants; significant results are bold and marked with an asterisk.

	Gender: LEN	Gender: EXT	Gender: ROC	Gender: LEN: EXT	Gender: LEN: ROC	Gender: EXT: ROC	Gender: LEN: EXT: ROC
Cold	*F(2,26)* = 1.99 *p* = 0.16	*F(1,13)* = 0.02 *p* = 0.88	*F(1,13)* = 0.58 *p* = 0.46	*F(2,26)* = 1.80 *p* = 0.19	*F(2,26)* = 0.31 *p* = 0.74	*F(1,13)* = 0.87 *p* = 0.37	*F(2,26)* = 0.07 *p* = 0.94
Warm	*F(2,26)* = 0.24 *p* = 0.79	*F(1,13)* = 1.38 *p* = 0.26	*F(1,13)* = 1.00 *p* = 0.34	*F(2,26)* = 0.09 *p* = 0.91	*F(2,26)* = 0.17 *p* = 0.84	*F(1,13)* = 2.19 *p* = 0.16	*F(2,26)* = 0.10 *p* = 0.90

Table 3.12: Experiment 2: Statistics for Time to Complete Lane Change with Gender as between subject factor; significant results are bold and marked with an asterisk.

3.4.6 Experiment 2 Discussion

This second experiment explored different stimuli designs and primarily investigated their influence on recognition rate and false positives at the return to neutral. No statistically significant difference was found to indicate an influence of any of the evaluated factors on the number of false positives. Therefore, *Hypotheses 1* and *2* could not be corroborated. There was also no influence of gender found on the number of false positives. The highest rate of false positives over all participants for cold and warm stimuli was discovered for *c-6-6-a* and *w-6-6-s*, respectively, with 17% each. The variation in number of false positives, both for the directions of change and gender gave no indication of what design factors influenced this value.

There were no gender differences found for recognition rates. Recognition rate for both cold and warm stimuli was influenced by the extent of temperature change: higher temperature changes increased the recognition for both directions of change. No other factor influenced the recognition for cold stimuli, whereas both extent and lengths of temperature change were important for recognition of warm stimuli. The higher temperature extent of 6°C led to a higher recognition, which corroborated *Hypothesis 3* only partly, as this effect was seen exclusively for warm temperature changes. Further exploration of the influence of LEN showed that recognition was reduced for warm changes of only 3°C, if the temperature was returned to neutral immediately after reaching the goal temperature. This, again, was only found for warm temperature changes, showing that a mirroring of stimuli in both directions of change might not lead to expected results.

No solution was found to both increase recognition and at the same time decrease the number of false positives: *w-6-6-a*, as the only feedback with a recognition rate of 100%, presented with 15% one of the highest numbers of false positives at the return to neutral. Designing thermal feedback for interaction with binary information of one device, therefore, has to be adapted to maximise the prioritised outcome.

Differences in task time, here represented by the time to complete lane change, might also influence the design process. While the lane change time was not influenced by any of the factors for cold stimuli, length and extent of temperature change had a significant effect for warm temperature changes. These findings again point out the discrepancy between cold and warm stimuli and the need to adapt the design depending on the preferred outcome.

3.5 Chapter 3 Discussion

Two experiments explored the usefulness of thermal feedback to convey binary directional information on a single device during driving. As this was the first investigation of thermal feedback during driving, the influence of the feedback on driving measures such as lane deviation, as indication of distraction, and recognition as a secondary task were one focus of the first experiment, in addition to time to complete lane change and subjective feedback, capturing the user ratings and workload. Lane deviation was found to not differ statistically from baseline driving with audio feedback. Recognition rates were high, with 97% and 88%, however, a surprising number of false positive identifications were made. Participants had problems differentiating between the return to neutral and a new stimulus. The time to complete lane change was increased by 1.82s for thermal feedback, when compared to the baseline of speech. This increased time requirement showed an unsuitability of thermal feedback for time-sensitive feedback. Significant differences between the genders were found here, which could indicate a slightly enhanced sensitivity of female participants towards thermal feedback. This conclusion was backed up by the higher number of false positives reported by women, but more research is needed for clarification. Workload showed no statistically significant difference. However, subjective ratings indicated that most participants found thermal feedback more complicated, which can be explained by both the novelty of the feedback and the additional mapping needed to translate direction of temperature change to direction of lane change. In addition, participants reported on a level of uncertainty connected to thermal feedback, which they did not experience for speech.

A second experiment was designed to explore a set of design aspects and evaluate their influence on recognition rate and false positives at the return to neutral. The parameters direction of change, length of cue presentation, extent of temperature change and rate of change at the return to neutral were investigated. Recognition rates varied, with one stimulus noticeably worse than all other, with a recognition rate of 58%. All other stimuli had recognition rates between 70% and 100%, the latter achieved by only one stimulus. The recognition rate was influenced by different parameters for warm and cold stimuli: while only extent influenced cold stimuli, length and extent of temperature change additionally influenced warm stimuli, as did their interaction. Design of thermal stimuli, therefore, cannot be simply mirrored for both directions of temperature change. No differences for gender were found, neither for recognition rate nor for false positives. None of the parameters had a statistically significant influence on false positives, which varied for stimuli between 2% and 17%. The stimulus with the highest recognition rate showed one of the highest numbers of false positives, illustrating that the design of thermal feedback will have to focus on optimising one of the aspects.
As there were no significant gender differences found for recognition or number of false positives in the second experiment, this line of investigation will not be pursued in the following experiments.

3.6 Conclusions and Research Question 1

The previously discussed two studies aimed to answer Research Question 1:

How accurately can thermal feedback give binary direction cues in an automotive setting (with one thermal device)?

The results show that the design of binary thermal directional cues has to be carefully considered. Some of the tested stimuli showed exceptionally high recognition rates, however, the problem of false positives highly impacted the accuracy of those cues. Additional lane changes occurred when the temperature changed back to neutral. Unfortunately, no solution could accommodate best results for both measures. For directional cues, this poses a considerable problem, as any false positives would be treated the same as the original cue, negating the desired effect by prompting a lane change into the original lane, or in the case of turn-by-turn navigation, lead to driver confusion and to potentially dangerous situations. An additional level of information will have to be added to ensure more robust directional cues. One possible solution could be adding spatial information to directional cues. This will require the use of at least two different thermal devices at different locations. The location of the thermal feedback could give the directional information while the design of the feedback could give information such as distance. Turn-by-turn navigation would benefit from such a design. Routes are usually planned in advance, providing a suitable use case for the less time-sensitive type of feedback. Chapter 4 explores such feedback for navigation with multiple thermal devices.

Chapter 4

Thermal Directional Cues with Multiple Devices on the Steering Wheel

4.1 Introduction

The previous chapter investigated the accuracy of binary directional cues provided by one thermal device. The binary feedback was found to have difficulties in conveying accurate directional cues, as the return to neutral was sometimes identified as an additional directional prompt. Spatial information, provided by more than one device, could help overcome this problem. The following two experiments have been designed to explore this aspect and aim to answer Research Question 2:

How accurately can thermal feedback give direction cues in an automotive setting with the spatial information from multiple thermal devices?

The directional cues have been changed from indicating simple lane changes to turn-by-turn navigation in a city environment, to provide a more complex and more realistic driving scenario. The thermal devices have been mounted on the steering wheel, to ensure constant contact with the hands and fixed spatial locations. Both experiments exploring this feedback will be described in detail in the next sections, followed by a conclusion in Section 4.5.

4.2 Experiment 3: Thermal Navigation

This user study compared thermal feedback on the steering wheel to audio feedback, as speech instructions, for turn-by-turn navigation. Speech was used as baseline, as it is the most common non-visual feedback type used for in-car navigation.

4.2.1 Methodology

The experiment was designed as a within-subjects study with one independent variable feedback type, being either thermal or audio. As navigation routes are often planned in advance, the use case was deemed to be suitable for the slowly increasing nature of thermal feedback and it was expected to perform as well as speech. While there were differences found for workload and subjective ratings in previous experiments, those might have been due to the additional mapping of direction of temperature change to direction of lane change. The addition of spatial information was hypothesised to alleviate these problems, as it eliminated the mapping. Driving performance in the previous experiments was not influenced by the feedback condition, observations in this study were not expected to be different. The mapping of destination direction to warm temperature changes was informed by the findings of Experiment 1, in addition to mappings used by both Wettach *et al.* [40] and Tewell *et al.* [134]. One of the goals of this experiment was to confirm this mapping. The hypotheses for this experiment, therefore, were:

Hypothesis 1: Thermal and auditory navigation cues will be equally effective in a navigation task;

Hypothesis 2: The workload and subjective rating for audio and thermal feedback will not differ significantly;

Hypothesis 3: The deviation from the ideal path will not differ significantly for the feedback types;

Hypothesis 4: The use of warm (opposed to cool) temperature changes to indicate the destination will be preferred by participants.

These questions were answered by investigating the dependent variables: stimulus recognition, deviation from the ideal path, perceived workload and subjective ratings. More detailed descriptions of the variables can be found in Section 4.2.5 *Measures*.

4.2.2 Apparatus

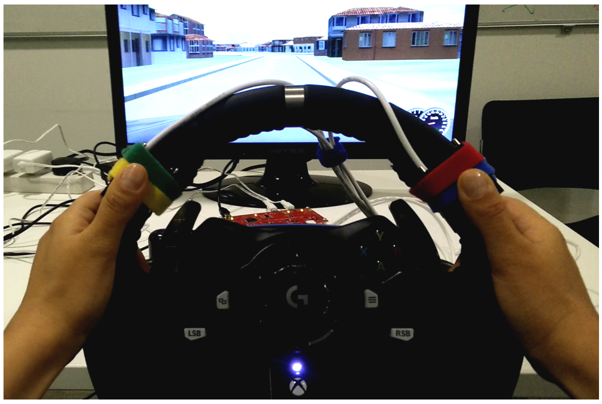
For this experiment, four smaller 1x1cm Peltier devices were used, see Figure 4.1(a). The devices were attached to the steering wheel using Velcro cable binders, see Figure 4.1(b): two on each side of the steering wheel (Figure 4.2(a)). They were positioned in a way that one device was facing the driver, while the position of the other was mirrored on the back of the steering wheel. In this way, the devices on one side could be touched by the thumb and the index finger of the same hand, leaving the rest of the hand free to hold the steering wheel, ensuring a comfortable grip, as seen in Figure 4.2(b). The Peltier control board was controlled via USB and built by SAMH Engineering, for details please consult

(a) 1x1cm Peltier device (gold) attached to heat-sink (black)

(b) Peltier device mounted on steering wheel with Velcro cable binders

Figure 4.1: Experiment 3: Hardware.

(a) Steering Wheel



(b) Experimental Setup

Figure 4.2: Experiment 3: Steering Wheel and experimental setup.

Appendix A.1.2. The rest of the technical setup was identical to Experiment 1 and 2, apart from the driving scenario: instead of a five-lane motorway the driving took place in a city environment, see Figure 4.3, also implemented in OpenDS 3.5 free version.

4.2.3 Driving Task and Feedback

In this experiment, participants followed instructions for turn-by-turn navigation in a simulated city environment. The driving instructions were kept as simple as possible: follow the road straight ahead in the right-most lane, until the feedback indicates the turning point; then turn into the next upcoming road on the side pointed to by the feedback.

The speed of the car was fixed to 30km/h, no pedals were provided. While the lack of braking capabilities for turning scenarios was slightly unnatural, the control of driving variation was

(a) City environment, suburbs

(b) City environment, downtown

Figure 4.3: Experiment 3: Simulator environment, implemented in OpenDS.

deemed more important in order to secure a valid comparison of the feedback types. 30km/h was found to be slow enough to turn, yet still represented a valid speed limit in European cities.

The simulator environment used was set for right-side driving and was kept unchanged, as the number of participants used to right-side driving in previous experiments exceeded the number of participants used to left-side driving. The car was reset to a different location after each turn, always back in the right-most lane, so even participants who were used to left-side driving were regularly reminded to keep on the right. This resetting approach was, however, mainly chosen to overcome the difficulties of implementing rerouting algorithms for the limited map space of the simulation environment and to ensure comparable turning points for both feedback types. After each reset, the participants had ample time to settle back into driving, before any new feedback was presented. In order to simulate standard navigation systems, the turning instructions were given in two steps: first by an initial ahead notification 200m before the turn, and then again when the turning point was reached. To capture the recognition of the ahead warnings, participants were asked to pull the gear paddle on the steering wheel on the side of the upcoming turn. Wrong turns were possible at any point, resetting the car for the next turn.

The turning points themselves were selected to represent the four major types of junctions and crossing: T-junctions, crossings (see Figure 4.3), right-only and left-only junctions. One turn of each type was chosen for the training sessions to introduce the feedback, while three of each were presented in random order for the main driving task. The training set was the same for both feedback types, while two different sets of twelve turns were used for the main driving tasks, counterbalanced over the feedback types and order of use. The drive towards each turning point usually passed several junctions and crossings, so the route could not be guessed without the feedback presented.

The speech instructions given to participants were spoken by a synthesised female voice and consisted of *Turn right/left in 200 metres* and *Turn right/left* when the turning point was reached.

The thermal feedback, see Figure 4.4, started from the neutral temperature of 30°C for all devices. 200m before the turn, the devices on both sides of the steering wheel changed their temperature for an extent of 6°C with a rate of change of 3°C/s. On the turning side, the devices warmed for 6°C (Figure 4.4 red line), while they cooled 6°C on the opposite side (Figure 4.4 blue line). This temperature was presented for 3s and then turned off, see black line in Figure 4.4.
When the turning point was reached, the feedback started the same, but the temperature was presented until the turn was completed and then returned to the neutral temperature. In this design, the distance to the turning point was encoded by length of temperature presentation,

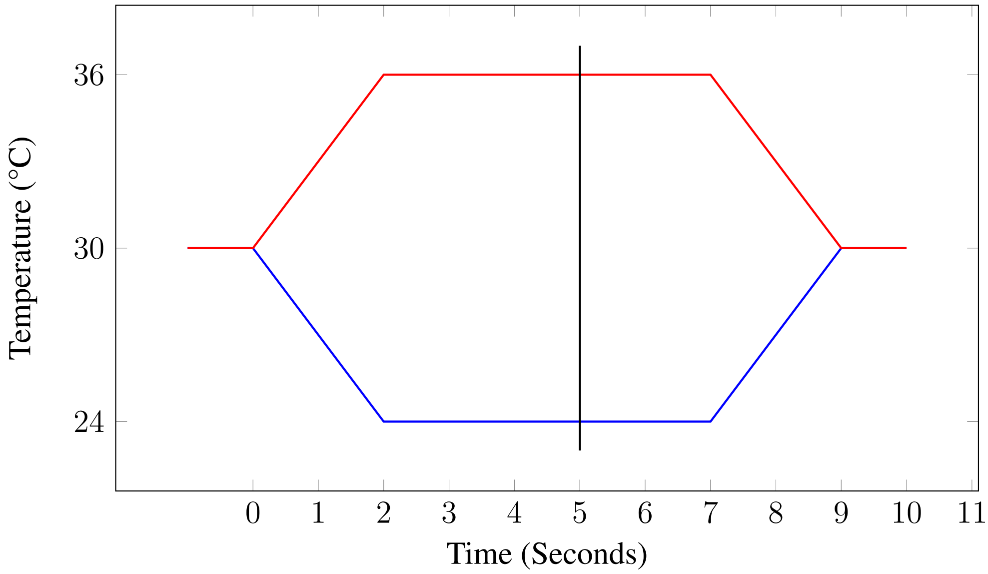


Figure 4.4: Experiment 3: Thermal feedback.

the short burst an ahead notification of the upcoming turn. The simultaneous presentation of warm and cold stimuli was expected to aid the recognition of the direction of temperature change, as the temperature difference between both hands would be increased and should be easier to recognise.

4.2.4 Participants and Procedure

Thirteen participants completed the experiment. They all held a valid driving license, all but one were right-handed. Four participants obtained their driving licenses in countries with right-side driving. None reported sensory impairments in the hands and all had at least corrected vision. For more details and on prior experience with the technologies (on 5- point Likert scale with 1 being no experience), consult Table 4.1.

Number of Participants	Age (Years)	Driving Experience (Years)	Experience Simulator	Experience Audio	Experience Thermal
13 (Female: 6 Male: 7)	*R*: 19-38 *M* = 25.38; *SD* = 5.24	*R*: 1-11 *M* = 4.88 *SD* = 3.11	*R*: 1-5 *M* = 2.23 *SD* = 1.48	*R*: 1-4 *M* = 2.92 *SD* = 0.86	*R*: 1-5 *M* = 1.85 *SD* = 1.28

Table 4.1: Experiment 3: Participant data, showing range (*R*), mean (*M*) and standard deviation (*SD*).

Participants were students and staff recruited through email lists, university online platforms and the participant pool provided by the School of Psychology of the University of Glasgow. The participants were welcomed to the School of Computing Science at the university, where

the experiments were conducted. They were presented with an information sheet, signed a consent form and filled in a questionnaire, capturing some demographic data such as gender, age and years of driving experience. In addition, they rated their experience with the technologies and were asked to choose their preferred mapping of direction of temperature change to destination direction.
Participants were given up to 5min to drive through the city environment freely, to get familiar with the driving setup. This was followed by the training phase of the first condition, consisting of four turns, succeeded by the main driving task with 12 turns, arranged in random order. After filling in the NASA TLX questionnaire and some additional ratings, the procedure was repeated for the second feedback type. At the end of the experiment participants filled in an additional questionnaire, capturing ratings and inquiring what temperature mapping participants would prefer after having finished the experiment with our design.

The documents used during this experiment can be found in Appendix A.4. The experiment design was approved the Ethics Committee of the College of Science and Engineering of the University of Glasgow. Participants were paid £6 for completing the one hour experiment.

4.2.5 Measures

The effectiveness of the feedback types was evaluated by comparing the recognition rates of both the 200m warnings and the actual turns.
NASA TLX questionnaires were used to capture the perceived workload, while ratings on a 5-point Likert scale asking how pleasant, comfortable, disruptive and complicated the feedback felt was used for additional subjective feedback. At the end of the experiment, participants were asked to rate how much they liked the feedback types on a 10-point Likert scale.

The influence on the driving behaviour was calculated by observing the deviation from an ideal path. The ideal path followed the road along the centre of the right-most lane, until the turn was made. The road leading towards the turn was usually not perfectly straight and had crossings and junctions (see Figure 4.3(b)). This fact, in addition to the complex city map, made an easy calculation of lane deviation, as used in the previous experiments, impossible. This alternative was used to enable a comparison between the two feedback types. The deviation was calculated using the Root Mean Square Error (RMSE) of the ideal path and the participant's driving path. 8s of driving both before and after the stimulus start were compared for the 200 metres ahead warnings. The turns themselves were not compared, as the deviation would be too heavily influenced by wrong turns or differing turn strategy in the simulator environment without braking (such as moving the vehicle slightly towards the middle of the road before turning).

To confirm the mapping of direction of temperature to turn direction, participants were asked about their preference at the beginning of the experiment. This was not asked directly, participants were rather presented with the following scenario:
In the following experiment, you will be presented with thermal feedback for navigation purposes on the steering wheel, where the device of one side of the wheel will be warmed, while the other side will be cooled.
Please decide: If the right side of the steering wheel was warmed, while the left side was cooled, I would turn to the: Left / Right
In the questionnaire at the end of the experiment, they were asked their opinion again, more direct this time:
Having finished the experiment, which direction would you turn towards, if presented with thermal feedback for navigation purposes? Warm / Cold. Participants were asked twice to see if the use of the feedback during the experiment would alter their preference. In addition, open questions asked for possible locations and use cases in an in-car environment.

4.2.6 Results

The data were compared using paired t-tests (*t(df)*), if they were normally distributed, and paired Wilcoxon tests (V) otherwise. Results of the perceived workload parameters *Physical Demand* and *Performance* differed from previously published work due to the reanalysis of the data.

Recognition

The ahead warnings were correctly recognised 94% in the thermal and 100% in the audio condition. The recognition rate for the turns was 91% and 100% for thermal and audio, respectively. Nine ahead warnings and thirteen turns were interpreted incorrectly in the thermal condition. This difference between feedback types was found to be significant with Wilcoxon tests for both ahead warnings ($V = 0$, $p = 0.03$) and turns ($V = 0$, $p = 0.01$).

Subjective Data

The comparison of workload with Wilcoxon tests showed significant results for overall workload ($V = 1$, $p = 0.002$). The more detailed analysis for the different workload parameters can be seen in Table 4.2, their values are presented in Figure 4.5. All parameters apart from Physical Demand and Performance showed significant differences, with thermal navigation rated more negatively than speech.

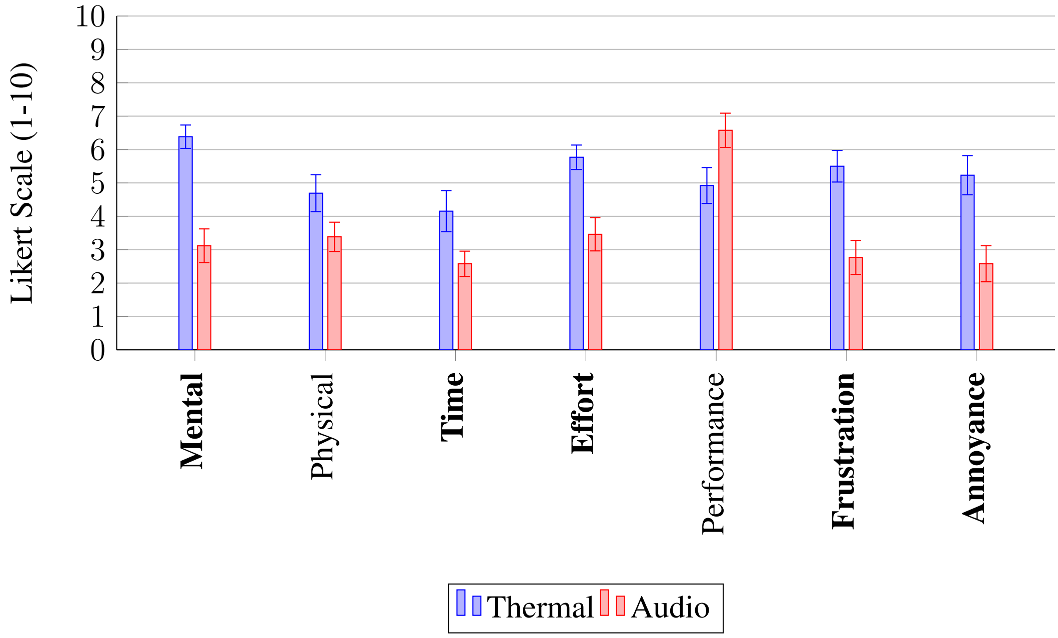


Figure 4.5: Experiment 3: Perceived workload; significant results are in bold font.

Mental Demand	Physical Demand	Time Effort	Effort	Perfor-mance	Frustra-tion	Annoy-ance
$V = 0$ **p = 0.001***	$V = 14$ $p = 0.05$	$V = 10$ **p = 0.02***	$V = 3.5$ **p = 0.005***	$V = 64$ $p = 0.05$	$V = 5$ **p = 0.005***	$V = 6$ **p = 0.01***

Table 4.2: Experiment 3: Statistics for NASA TLX rating of workload; significant results are bold and marked with an asterisk.

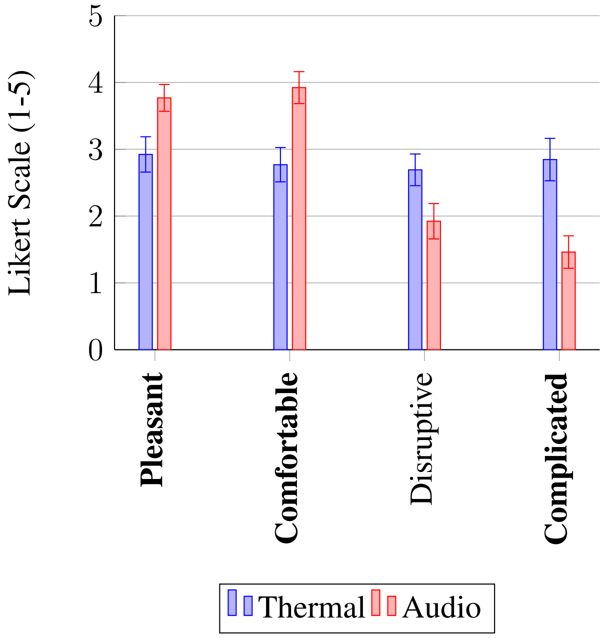


Figure 4.6: Experiment 3: Subjective Additional Ratings; significant results are in bold font.

Pleasant	Comfortable	Disruptive	Complicated
V = 58 **p = 0.02***	V = 42 **p = 0.02***	V = 4.5 p = 0.06	V = 7.5 **p = 0.01***

Table 4.3: Experiment 3: Statistics for Subjective Additional Ratings; significant results are bold and marked with an asterisk.

The values for the additional subjective ratings can be found in Figure 4.3, the statistical data of the Wilcoxon tests in Table 4.3. The parameters Pleasant, Comfortable and Complicated showed significant differences, favouring speech feedback, but not Disruptive.

The comparative rating at the end of the experiment showed significantly better rating for audio feedback (V = 76, p = 0.004): median(audio) = 7.5, median(thermal) = 3).

Participant comments indicated that the audio feedback was considered to be *simple* (*P09*, *P11*, *P12*, *P13*, *P07*), *clear* (*P03*, *P10*, *P12*, *P13*), *easy* (*P08*, *P06*, *P04*) and *familiar* (*P02*, *P07*, *P11*), but also *disruptive* (*P01*). Thermal feedback was described as *difficult* (*P02*, *P03*, *P07*, *P13*), *requiring more concentration* (*P06*, *P08*, *P11*, *P12*), *varying in sensation* (*P02*, *P11*) and *confusing* (*P05*). *P04* commented: *I felt like sometimes my brain just registered intensity of temperature rather than intense heat or intense cold* and *P05* mentioned that it was *sometimes difficult to tell hot from cold. Often felt hot all the time*. *P07* reported similar problems: *I felt it was difficult at times to tell the difference between the hot and cold feedback and I really had to think about it. I may well have turned the wrong way once or twice.* While many participants conveyed a sense of overall uncertainty concerning thermal feedback, it was also described as *pleasant and soothing* (*P10*) and not *as disruptive* (*P01*). Several participants mentioned the uncomfortable hand position required for thermal feed-

Thermal Before - Audio Before	Thermal After - Audio After	Thermal Before - Thermal After	Audio Before - Audio After
$V = 80$; **$p = 0.01$***	$V = 74$ **$p = 0.048$***	$V = 0$ **$p < 0.001$***	$V = 1$ **$p < 0.001$***

Table 4.4: Experiment 3: Statistics for Deviation from Ideal Path; significant results are bold and marked with an asterisk.

back as a factor of their rating (*P02*, *P03*).

P02 named a few use cases for thermal feedback in the car: *more emergency things. An ambulance approaching from behind, a collision ahead, a stop sign or red light ahead perhaps. Or maybe if you are breaking speed limit.* The idea of collision warning was shared by *P09*. Others had suggestions related to temperature: *Engine overheating warning* (*P03*), *air-conditioning* (*P08*) and *current temperature setting. [...] Road ice or grip/traction conditions so I know to drive more carefully* (*P11*). Distance to destination (*P11*) and low fuel (*P06*) were named in addition. *P03* suggested to present thermal feedback on the *door handle if you leave electronics on when leaving*. Seat (*P07*), pedal (*P09*), side/shoulder (*P10*) and aircon dial (*P11*) were named as possible locations for thermal feedback.

Deviation from Ideal Path

The deviation from the ideal path was compared between the feedback types, both before and after the stimulus onset, as well as within the conditions. All comparisons with Wilcoxon tests showed significant results, see Table 4.4. The deviation in the thermal condition was significantly higher than in the audio conditions and within both condition the deviation after the presentation of the feedback was higher than the deviation before, see Figure 4.7.

Direction Mapping

When asked about the mapping at the beginning of the experiment, eight participants stated they would turn towards the warm side, five towards the cold. After the experiment, eleven stated that they would now turn towards the warm, while two participants stated, they would turn towards the cold. Interestingly, one of those two changed their answer after the experiment from warm to cold.

4.2.7 Experiment 3 Discussion

This experiment explored thermal feedback for turn-by-turn navigation and compared it to speech feedback. Recognition rates for thermal feedback were high, 94% and 91%, but they

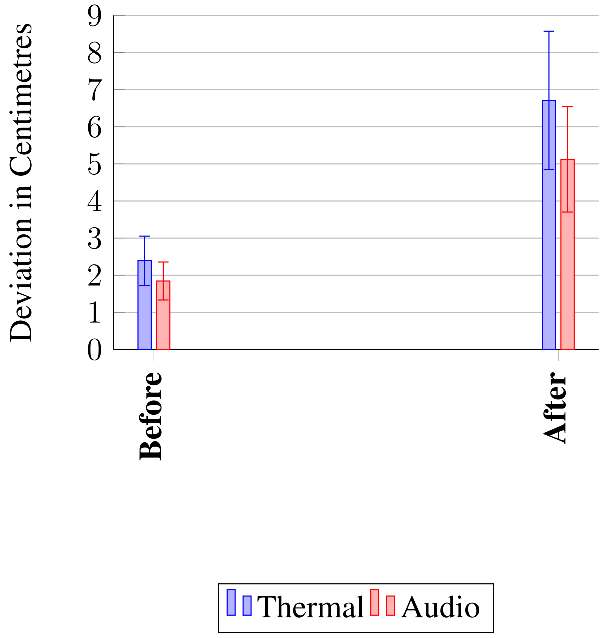


Figure 4.7: Experiment 3: Deviation from Ideal Path; significant results are in bold font.

were still statistically significantly worse than speech with a recognition rate of 100%. *Hypothesis 1* claiming they would show equal efficiency, therefore, could not be corroborated. The novelty of the feedback and inherent difference of perception for audio and haptic feedback, made a direct comparison of the two feedback types complex. The comparison of thermal with another haptic condition might give a better understanding of the efficacy and usefulness of the feedback.

Furthermore, both perceived workload and three of four additional subjective ratings showed statistically significant differences between the feedback types, so *Hypothesis 2* could not be corroborated either. Participants reported general uncertainty and increased need for concentration for thermal feedback. Both sentiments would be increased by the novelty of the feedback. They also commented that the simultaneous temperature change on both sides of the steering wheel confused rather than enforced the identification. Temperature change of only one side of the steering wheel might aid in decreasing the confusion and increase recognition and ratings. Furthermore, participants commented on differences of hand positioning needed for the feedback types and named this as contributing factors for the rating. The comparison with a feedback type with similar physical constraints could balance this factor.

The deviation from the ideal path was different for the two feedback types, not corroborating *Hypothesis 3*. Thermal feedback had a higher deviation than audio, mirroring the comments and workload ratings and indicating more distraction posed by the novel thermal feedback, compared to the familiar speech. Both feedback types showed higher deviation after being presented with the feedback. This might be slightly influenced by the paddle pull, with which participants indicated their recognition. While more participants in this experiment were used to left-side driving, none commented on encountering problems with driving on the right side.

Hypothesis 4, claiming the mapping of warm temperature change to destination would be preferred by most, was proven correct: eight out of thirteen participants stated they would prefer to turn toward the warm side at the beginning of the experiment and even more confirmed the mapping after the experiment, with all but two agreeing with the mapping.

The findings of this experiment suggested that a change in thermal design is needed to improve the navigation efficiency. A follow up study therefore explored an improved design, comparing it to another tactile feedback type, which would allow for the design of more similar feedback and presentation conditions.

4.3 Experiment 4: Haptic Navigation

Thermal feedback for navigation with an altered design was compared to another haptic feedback type in this experiment: cutaneous push [210]. This is feedback elicited through retractable solenoid pins embedded in a steering wheel.

4.3.1 Methodology

The within-subjects study had one independent variable: feedback type, consisting of thermal and cutaneous push feedback. These two tactile modalities could be presented at the same location on the steering wheel and would both be equally unfamiliar to the driver, as cutaneous push feedback had not been tested for navigation purposes in the past. The comfort rating of both was, therefore, expected not to be different. In addition, no difference in performance was expected, as both feedback types utilised the same sensory channel, while addressing different receptors in the skin. The change in thermal feedback design was expected to improve the performance compared to the previous experiment. The hypotheses for this study were:

Hypothesis 1: *Thermal and cutaneous push navigation cues will be equally effective in a simulated navigation task;*

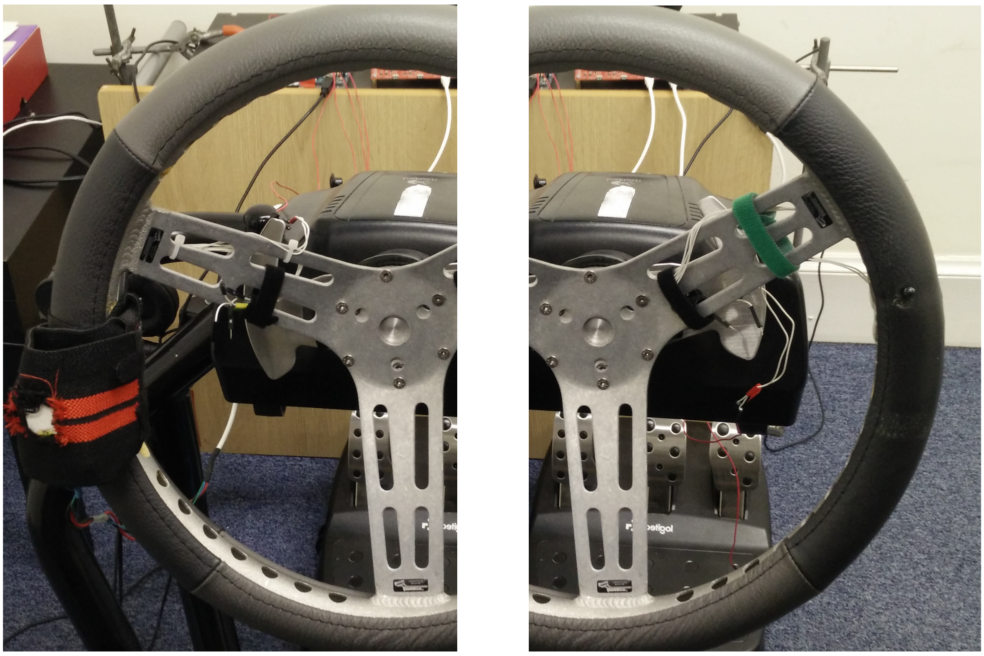
Hypothesis 2: *The subjective rating of comfort of cutaneous push feedback and thermal will not differ;*

Hypothesis 3: *The simplified design of the second thermal navigation feedback will perform better than the design in Experiment 3.*

Recognition rates will be evaluated to determine the effectiveness of the feedback. Perceived workload and additional subjective ratings will be explored, as will the deviation from the ideal path. Some data will in addition be compared with results of Experiment 3, to determine if the design changes of the thermal feedback increased performance. More details of the dependent variables will be discussed in Section 4.3.5 *Measures*.

4.3.2 Apparatus

This experiment utilised 2x2cm Peltier devices, as were used in Experiments 1 and 2, see Figure 4.10(a), controlled via USB boards, as in Experiment 3. One device was attached to the steering wheel on each side with sports bands and could be grasped with the hand, ensuring the Peltier would touch the palm of the hand, see Figure 4.8(a).



(a) Thermal Steering Wheel (b) Cutaneous Push Steering Wheel

Figure 4.8: Experiment 4: Steering Wheel.

The steering wheel consisted of a pre-drilled metal steering wheel[1], mounted onto a Logitech G27 racing wheel base. One Push Action Tubular Solenoid[2] was embedded into each side, see Figure 4.8(b). The solenoids were retracted into the steering wheel and could protrude to gently tap the drivers palm, see Figure 4.9. Small plastic balls taken off sewing needles topped the solenoids to ensure comfort. The cutaneous push feedback was controlled with an Arduino Uno board connected through USB.

Participants were seated in an RSeat RS1 gaming racing chair[3], with the steering wheel attached securely in front of them. Logitech racing pedals were placed on the ground under

[1] http://www.longacreracing.com/products.aspx?prodid=7620, accessed 06/04/2020

[2] https://uk.rs-online.com/web/p/dc-d-frame-solenoid/2501280/, accessed 06/04/2020

[3] http://www.rseat.net/rs1-racing-cockpit/rs1-m4a-black/, accessed 30/09/2020

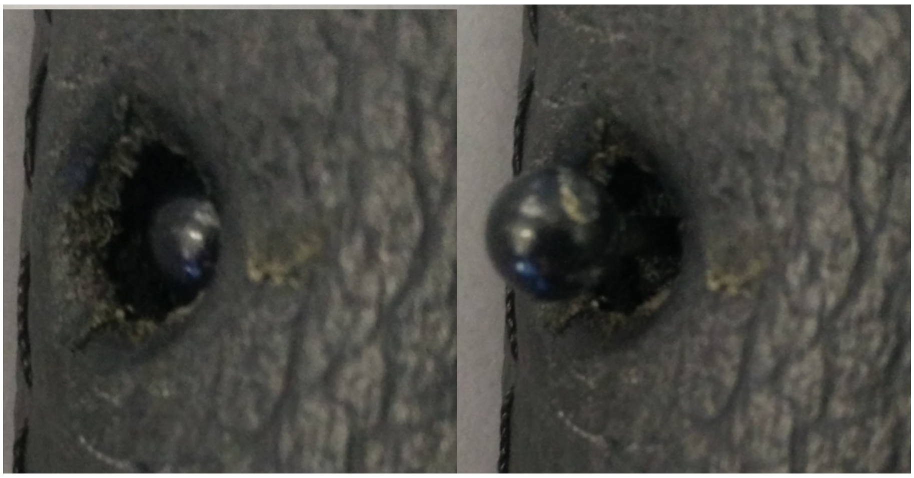


Figure 4.9: Experiment 4: Solenoid embedded into the Steering Wheel for Cutaneous Push Feedback.

(a) Peltier Device

(b) Experimental Setup

Figure 4.10: Experiment 4: Peltier device and setup.

the steering wheel. The driving environment was the same as in Experiment 3 and projected onto the wall of the usability lab using a BENQ DLP projector attached to a Windows desktop computer. Sennheiser HD 25 Basic Edition headphones played driving noises throughout the experiment. The complete setup can be seen in Figure 4.10(b).

4.3.3 Driving Task and Feedback

The driving task in this study was the same as in Experiment 3. The same training set was used, as were the two sets of turns, again counterbalanced. The thermal feedback was changed, however, and only showed warm feedback on the turning side. 200m before the turn, the device warmed 6°C from the neutral temperature of 30°C with a rate of change of 3°C/s. This temperature was presented for 6s and then returned with a rate of change of 1°C/s, see Figure 4.11. The feedback at the turning point was of the same design, but the temperature of 36°C was presented until the turn was completed.

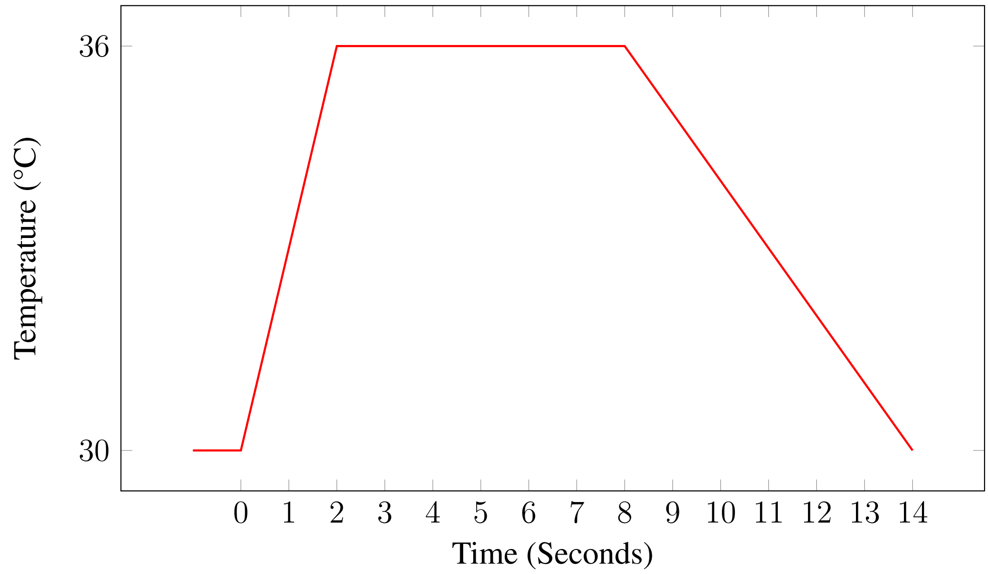


Figure 4.11: Experiment 4: Thermal feedback.

The cutaneous push feedback for the 200m ahead warning was adapted from the thermal feedback: the pin protruded from the steering wheel on the turning side and stayed in this position for 6s, before retracting into the steering wheel again. When the turning point was reached, the pin protruded and retracted rhythmically with a frequency of 1s until the turn was completed.

Participants were asked to use the foot pedals to indicate the turning direction after the first warning. The brake pedal indicated a turn towards the left side, and the accelerator pedal a turn towards the right side. The clutch pedal was not used, as the pressure setting differed from the other two, and the separated location made the use of the other two pedals easier and more comfortable. This approach was adapted as the steering wheel was bigger and the gear paddles could not be reached easily, especially in the thermal condition, and to eliminate any influence of the paddle pull on the deviation of the ideal path.

4.3.4 Participants and Procedure

Seventeen participants were newly recruited for the experiment. All participants held a valid driving license, six of them were obtained in right-side driving countries. Two participants were left-handed, all others right-handed. No participants reported sensory impairments in their hands and all had at least corrected vision. Their experience prior to the study (on 5-point Likert scale with 1 being no experience) and more detailed demographic data can be found in Table 4.5.

Number of Participants	Age (Years)	Driving Experience (Years)	Experience Simulator	Experience Cutaneous Push	Experience Thermal
17 (Female: 10 Male: 7)	*R*: 20-65 *M* = 29.00 *SD* = 10.35	*R*: 1-45 *M* = 9.12 *SD* = 10.49	*R*: 1-4 *M* = 2.35 *SD* = 1.17	*R*: 1-4 *M* = 1.65 *SD* = 1.06	*R*: 1-4 *M* = 1.53 *SD* = 0.94

Table 4.5: Experiment 4: Participant data, showing range (*R*), mean (*M*) and standard deviation (*SD*).

Participants were recruited through email lists and the participant pool of the School of Psychology and consisted of students and staff. The participants were welcomed in a university room of the School of Computing Science and presented with the information sheet and the consent form they signed. They were seated and presented with the first feedback type, followed by the training set. During the training, participants did not wear headphones, instead they were actively guided by the experimenter. The main driving task of the first feedback task followed, during which participants were presented with driving noises via headphones. After filling in a questionnaire, the procedure was repeated with the second feedback type. At the end of the experiment, participants filled in an additional questionnaire. Affirmation for the association of warm to destination was sought again. Participants received £6 at the end of this one hour experiment. Please see Appendix A.5 for more details of the documents used. The experiment was approved by the Ethics Committee of the College of Science and Engineering of the University of Glasgow.

4.3.5 Measures

The recognition rates were collected for both the first warnings 200m ahead of the turn, indicated by the pedal presses, and the turns themselves.

Perceived workload and subjective rating were collected through questionnaires after each driving task, consisting of the NASA TLX questionnaire and additional subjective feedback asking how pleasant, comfortable, complicated and disruptive the feedback felt. Another questionnaire was presented at the end of the experiment, capturing demographic data, ratings and ideas for further use of thermal feedback.

As in Experiment 3, the deviation from the ideal path was calculated as the Root Mean Square Error between the ideal path and the position of the participant's car of the 8s before and after the first warning 200m before the turn.

The comparison between the thermal designs of the first and second navigation experiment was evaluated for the recognition and the subjective ratings. As two different steering wheels had to be used for the two experiments, it could not be excluded that the deviation from the

Mental Demand	Physical Demand	Time Effort	Effort	Perfor-mance	Frustra-tion	Annoy-ance
$V = 0$ **$p < 0.001$***	$V = 15$ **$p = 0.04$***	$V = 25$ **$p = 0.03$***	$V = 12$ **$p = 0.002$***	$V = 103.5$ **$p = 0.01$***	$V = 13.5$ **$p = 0.009$***	$V = 12$ **$p = 0.007$***

Table 4.6: Experiment 4: Statistics for NASA TLX rating of workload; significant results are bold and marked with an asterisk.

ideal path might be influenced by differences in steering wheel sensitivity and hardware behaviour.

4.3.6 Results

The data were evaluated using paired t-tests (*t(df)*), if the data were normally distributed, and paired Wilcoxon (V) otherwise and for subjective data. The comparison between the designs was evaluated with the unpaired versions of the tests.

Recognition

The ahead warnings had a perfect recognition of 100% for cutaneous push feedback and 97% for thermal feedback. Four thermal ahead warnings were missed. The recognition rate for the turns was 98% for cutaneous push and 87% for thermal feedback. Eight turns in the cutaneous push condition were made incorrectly. Most of these incorrect turns were made when participants prematurely turned into roads, which were already almost passed when the feedback started. These sudden turns were not made in the thermal condition. In the thermal condition, four 200m warnings were missed and 25 turns made incorrectly. Some of those turns occurred because participants turned when the 200m warnings were given. The difference between the feedback types with Wilcoxon tests was statistically significant for turns ($V = 4$, $p = 0.01$), but not ahead warnings ($V = 0$, $p = 0.35$).

Subjective Data

The overall perceived workload showed statistically significant differences with Wilcoxon tests between the conditions ($V = 9$, $p = 0.002$). More detailed evaluation showed that all parameters were significantly different, see statistical results in Table 4.6 and the parameter values in Figure 4.12. Cutaneous push feedback was rated more positively than thermal feedback for every parameter.

Subjective ratings for pleasantness, comfort, disruptiveness and complexity (see Figure 4.13) showed significant differences with Wilcoxon tests between the conditions for pleasantness

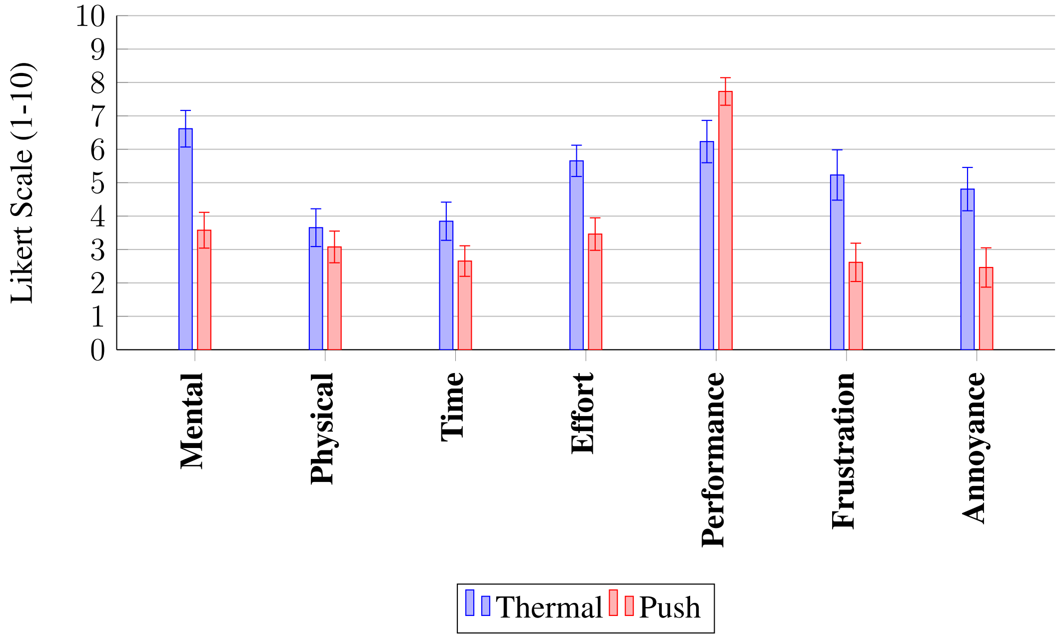


Figure 4.12: Experiment 4: Perceived workload; significant results are in bold font.

and complexity, see Table 4.7. Cutaneous push feedback was rated as more pleasant and less complicated than thermal feedback.

Pleasant	Comfortable	Disruptive	Complicated
$V = 33.5$ **$p = 0.03$***	$V = 51$ $p = 0.10$	$V = 42$ $p = 0.84$	$V = 0$ **$p = 0.003$***

Table 4.7: Experiment 4: Statistics for Subjective Additional Ratings; significant results are bold and marked with an asterisk.

At the end of the experiment participants rated thermal feedback significantly worse than cutaneous push feedback (median(push) = 9, median(thermal) = 2.5; Statistics with Wilcoxon tests: $V = 1$, $p < 0.001$)

Participants commented on the thermal feedback that they had to *actively pay attention to notice the temperature change* (*P14*), a view that was shared by *P02* and *P03*. Several participants noted that it often took them *a while to be completely certain the temperature was actually going up* (*P07*). *P07* commented further that they were *often uneasy at first if signal was given, so reaction time felt longer and required more focus on the navigation*, a feeling that was shared by *P17* and *P02*. *P01* wrote: *I found that after getting a thermal signal, that hand would feel odd, almost as if it was getting more thermal signals in the next task, even if it wasn't. I kept feeling the urge to press a pedal until the actual thermal feedback activated and was obviously the real feedback due to its intensity.* This uncertainty connected to thermal feedback, which was also voiced in the previous experiments, was mirrored here in comments from several other participants as well. *P12* wrote: *I sometimes*

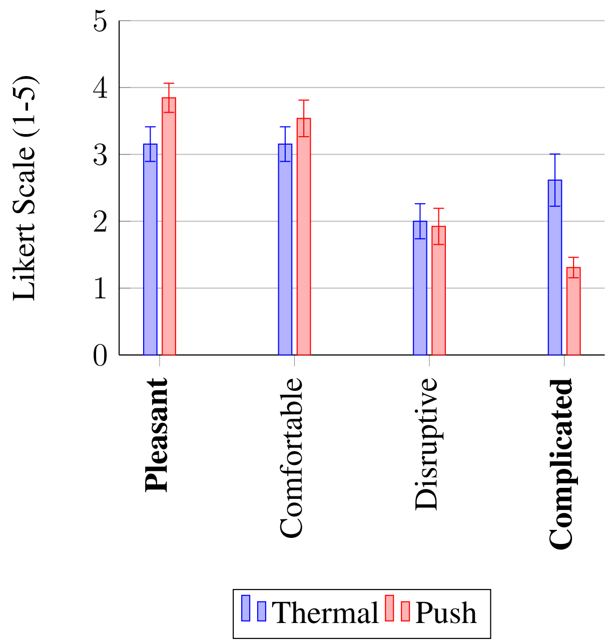


Figure 4.13: Experiment 4: Subjective Additional Ratings; significant results are in bold font.

wasn't sure whether the steering wheel was getting hot or whether it was just my hand and *P04* mentioned that they felt *too much mental hesitation or uncertainty regarding the warming up sensation*. *P01* commented that *The more I used it, the less clear it was what temperature I was feeling. Also sometimes the sensation snuck up on me.* The feeling of the warming itself was annotated with almost opposite remarks. *P05* noted that *the heat felt nice, but it was hard to detect / feel it for sure* and *P11* that *it felt nice, but [...] sometimes [...] difficult to detect*, while *P09* mentioned that thermal feedback *warms the palms, very annoying*. *P08* commented that they *found it less distracting than cutaneous feedback.*

The cutaneous push feedback on the other hand was mostly described as *easy* (*P01*, *P07*, *P10*, *P12*, *P14*, *P17*) and *clear* (*P01*, *P07*, *P11*). *P03* commented that there was *no need to pay attention to it - its sounds and feel similar to normal indicator, it feels more natural than the thermal one*. The lack of additional attention needed was mentioned also by *P07* and *P16*. The latter went on to write that they *didn't feel the pressure* they felt with thermal feedback. *P14* described the push feedback as if *it was almost like the car indicator was physically clicking*. While both *P01* and *P02* remarked on the non-disruptive nature of cutaneous push feedback, *P08* described it as *a bit disorientating*, their *instinct [...] to push the 'button' back into the wheel when given the 200m indication. P16* noted that *it could actually be beneficial as a disruptive feedback because if you are falling asleep it could save your life to feel the poke, instead of warm thermal feeling*. *P09* commented on a drawback of both feedback types: *The steering wheel [...] is really annoying and made me uncomfortable while driving as I had to keep both hands on the steering wheel at all times.*

Most participants suggested the use of thermal feedback on the seat (*P05*, *P09*, *P14*), *P13* suggested pedals. *P01* and *P08* agreed that the steering wheel already is the most appropriate location. The use case most often named was a warning when speeding (*P01*, *P02*, *P11*, *P13*). Several types of other warnings were suggested as well: handbrake-on warning (*P08*), front proximity warning (*P05*, *P09*), blind-spot warning (*P10*) or a general *emergency feedback [...] if any of the control lamps light up* (*P07*). Some of those were inspired by metaphors, such as the blind-spot warning, *as the person would give off thermal radiation in a literal sense, so would be appropriate* (*P10*) or *driving too fast. It would be useful, and it seems like a good metaphor (engine getting too hot or something...)* (*P11*). A different use was suggested by *P14*: *It could be used to draw attention to non-essential locations during the journey. E.g., alert to something like a service station. Or if the satnav knows I'm going to the shops or the bank, then the thermal could indicate that there's an alternative one nearby. So it's not really important if I recognise or not, but it's nice to become aware of that stuff if I do happen to feel it.*

Deviation from Ideal Path

The deviation from the ideal path was different within the two condition, with the deviation being smaller after the presentation of the feedback. The comparison with Wilcoxon tests between the conditions did not differ significantly, see Table 4.8 for statistical data and Figure 4.14 for values.

Thermal Before - Push Before	Thermal After - Push After	Thermal Before - Thermal After	Push Before - Push After
$V = 75$ $p = 0.96$	$V = 85$ $p = 0.71$	$V = 135$ $\mathbf{p = 0.003}$*****	$V = 148$ $\mathbf{p < 0.001}$*****

Table 4.8: Experiment 4: Statistics for Deviation from Ideal Path; significant results are bold and marked with an asterisk.

Comparison of Thermal Feedback Design

Comparing the two thermal designs of Experiment 3 and 4 showed no statistically significant differences with Wilcoxon tests, see Table 4.9 for the perceived workload statistics and Table 4.10 for additional ratings and recognition statistics.

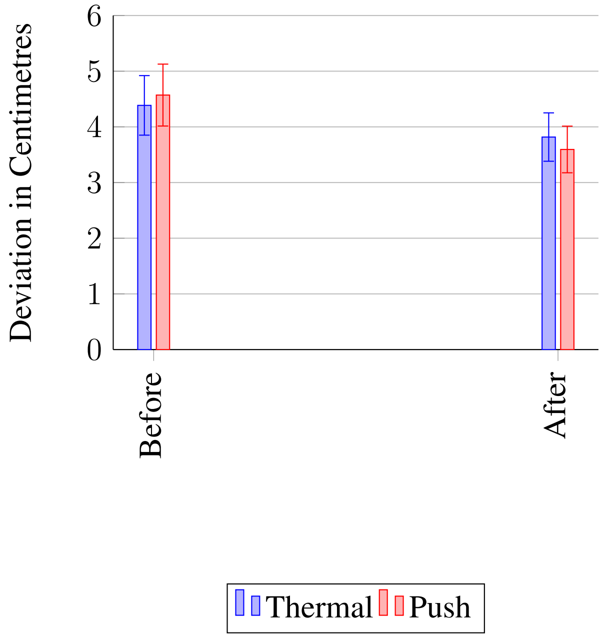


Figure 4.14: Experiment 4: Deviation from Ideal Path; significant results are in bold font.

Mental Demand	Physical Demand	Time Effort	Effort	Performance	Frustration	Annoyance
$V = 76.5$ $p = 0.16$	$V = 133.5$ $p = 0.34$	$V = 111$ $p = 1.00$	$V = 101$ $p = 0.70$	$V = 67$ $p = 0.07$	$V = 112$ $p = 0.97$	$V = 132$ $p = 0.39$

Table 4.9: Experiment 3 and 4: Statistics for the Comparison of NASA TLX rating of workload; significant results are bold and marked with an asterisk.

Pleasant	Comfortable	Disruptive	Complicated	Rating	Warnings	Turns
$V = 94.5$ $p = 0.49$	$V = 78.5$ $p = 0.17$	$V = 153$ $p = 0.06$	$V = 123.5$ $p = 0.59$	$V = 119$ $p = 0.74$	$V = 75.5$ $p = 0.06$	$V = 111$ $p = 1.00$

Table 4.10: Experiment 3 and 4: Statistics for Comparison of Subjective Additional Ratings; significant results are bold and marked with an asterisk.

4.3.7 Experiment 4 Discussion

In this simulator experiment thermal feedback was compared to cutaneous push feedback in the context of turn-by-turn navigation in a city environment. The 200m ahead warnings were equally well understood and their recognition reported in both feedback types. The different recognition rates of 97% in the thermal and 100% in the push condition were not statistically significantly different. The main turning events, however, showed a significant difference between the recognition rate of 87% in the thermal and 98% in the cutaneous push condition, negating the predictions made in *Hypothesis 1*. While participants reported that they felt their reaction time was longer for thermal feedback, the wrong turns made in the cutaneous push condition were due to the opposite effect: some participants turned too early, manoeuvring the car into roads that were already mostly passed at the onset of the feedback. This led to situations which would be highly dangerous in real life scenarios.

These sudden reactions were not observed in the thermal condition, suggesting that the feedback was experienced as calmer and less abrupt. This was reflected by only one participant in their comments, however. Most participants reported that cutaneous push feedback was easier and left them feeling more relaxed, as they did not have to invest as much attention to the feedback. This sentiment was mirrored in the subjective ratings, both for perceived workload, with cutaneous push feedback rating significantly better for all parameters, and the additional ratings, where both pleasantness and complexity were rated significantly better. Ratings for disruptiveness and comfort showed no significant difference, so no conclusions can be drawn on *Hypothesis 2*. The presentation of both tactile feedback types at the same location on the steering wheel might have levelled this parameter. However, one participant noted on how the need to keep both hands on the steering wheel throughout made them feel annoyed and uncomfortable.

The change in the thermal design for Experiment 4 showed no statistical difference when compared to Experiment 3, not corroborating *Hypothesis 3*. Neither recognition rates, nor subjective ratings showed significant improvement by the change in design and the presentation of thermal feedback on only one hand. The change between the thermal design from Experiment 3 to Experiment 4 was accompanied by a change of hardware as well: four 1x1cm Peltier devices were swapped with two 2x2cm devices. This further changed the location of the feedback presentation: while thermal feedback was presented on the fingertips of index finger and thumb in Experiment 3, this was changed to the thenar region of the palm for Experiment 4, a slightly more perceptive part of the hand for tactile feedback. While this change influenced the direct comparability of the thermal designs, the changes were made to ensure a better mirroring of thermal and cutaneous push feedback in Experiment 4 and therefore to increase the comparability of those two tactile feedback types.

4.4 Chapter 4 Discussion

Thermal feedback was explored with multiple devices on the steering wheel for turn-by-turn navigation in two user experiments. While recognition rates were high with 87% to 97%, navigation with speech or cutaneous push feedback still outperformed thermal feedback for the actual turns, but not the 200m warnings for the second experiment. The presentation of warm and cold stimuli simultaneously in Experiment 3 was described as confusing, but the change to presentation of only warm stimuli on one hand did not seem to improve the recognition significantly. Furthermore, thermal feedback was continuously described as more demanding as both audio and cutaneous push feedback, mostly due to uncertainty connected to thermal feedback that was not reported for either audio or cutaneous push feedback. This could partly be a side effect of the novelty of thermal feedback. While cutaneous push also represents a novel feedback type, the idea of being pushed or tapped as feedback is more ubiquitous then being actively warmed up or cooled down to present information other than the temperature of the item. However, comments indicated that they sometimes were not sure, if their hands naturally warmed on the steering wheel, an effect that would not influence either of the other feedback types used here. While warming seemed to be the more natural choice to direct movement, reinforced by results presented in this thesis, cooling might be a better choice to present at locations which would be held for a longer time. Warming might result naturally from holding something, the hands warming up the surface of the item being held, but a cooling sensation might be unexpected enough to overcome the uncertainty. In addition, long term use of thermal feedback would have to be tested, to explore how the detection of the feedback is influenced by longer exposure. One of the participants mentioned that uncertainty increased with longer use, rather than decreased as would be imagined with increasing familiarity.

An interesting difference between the tactile feedback types of Experiment 4 could be observed: while thermal feedback led to missed turns due to its unobtrusive nature, cutaneous push feedback led to participants reacting in a sudden and unexpected way: they turned into roads that had already been partly passed by the time the feedback started. This kind of immediate reaction might be unsuitable for navigational purposes, with sudden reactions leading to dangerous situations. Other use cases could easily be imagined in a driving environment, where the calmer nature of thermal feedback could be more suitable than the attention grabbing cutaneous push feedback, such as for non-urgent notifications.

4.5 Conclusions and Research Question 2

Two experiments with thermal devices attached to the steering wheel aimed to answer Research Question 2:

How accurately can thermal feedback give direction cues in an automotive setting with the spatial information from multiple thermal devices?

Both experiments used spatial information presented by the locations of the thermal devices on the steering wheel for turn-by-turn navigation cues. While thermal feedback was presented on both hands simultaneously in the first experiment, with directional cues given by the direction of temperature change presented, the second experiment only presented thermal feedback on one side, the presentation location itself informing the driver of the turning direction. Recognition rates were high, over 87%, showing that thermal feedback on multiple devices can be utilised to present directional cues. The presentation of warm and cold stimuli simultaneously was described as confusing. In line with feedback from the user experiments discussed in Chapter 3, participants reported an increased level of uncertainty when compared to audio and cutaneous push. Furthermore, they mentioned an increased need for paying attention, as is mirrored in the perceived workload ratings. Even with high recognition rates, the use of thermal feedback by itself might lead to unsatisfied and fatigued drivers if these ratings hold true even after familiarisation with the novel feedback. Longitudinal studies will have to explore this aspect.

The exploration of thermal feedback in combination with other tactile feedback, such as vibration, could lead to a decrease in perceived workload and take advantage of the familiarity of the second feedback type. As one of the use cases consistently suggested by participants, notifications present a suitable test bed for the investigation of this bimodal tactile aspect. Chapter 5 will therefore discuss experiments exploring bimodal thermal and vibrotactile notifications in a driving environment.

Chapter 5

Unimodal and Multimodal Notifications with Thermal Feedback

5.1 Introduction

The previous chapters investigated the use of unimodal thermal feedback for directional cues. This chapter will move away from this use case and explore more complex thermal feedback for notifications, both unimodal and in combination with vibration, as bimodal tactile feedback. Three experiments will aim to answer Research Question 3:

How effectively can thermal feedback convey notifications in a car in a
a. unimodal setting?
b. bimodal tactile setting?

In all three experiments, the feedback was presented on the steering wheel, enabling the driver in the simulated environment to safely keep both hands on the steering wheel. The focus of the notifications differs in all three experiments, to allow for a broader investigation and explore several useful combinations and use cases. In the first, the influence of thermal feedback on the feeling of urgency was explored, while the second investigated how easily several layers of information could be conveyed. The third experiment aimed to enrich multimodal feedback for transfer of control with bimodal tactile feedback. Section 5.6 will follow the discussion of all three experiments with a conclusion.

5.2 Experiment 5: Uni- and Bimodal Tactile Notifications with Different Levels of Urgency

In this experiment, the effectiveness of thermal and bimodal tactile feedback for notifications was tested with the affective association of urgency embedded into the feedback. Thermal and vibrotactile feedback was presented unimodally and as bimodal combination, encoding different levels of urgency. The same urgency levels were encoded in all modalities, leading to redundant information presentation in the bimodal condition.

5.2.1 Methodology

The experiment was designed as a 5x3 within-subjects user study, with Modality (Bimodal Warm, Bimodal Cold, Thermal Warm, Thermal Cold, Vibration) and Urgency (High, Medium, Low) as the independent variables.

The influence of the thermal modality on the feeling of urgency and the identification rate and time during driving were investigated to evaluate how effective notifications of different urgency levels can be conveyed. The combination of the two feedback types, thermal and vibrotactile, was expected to increase the feeling of urgency. Adding temperature changes, which have been shown to increase dominance and arousal, to the already attention-grabbing vibrotactile cues would have an influence on the perceived urgency. Due to the slowly increasing thermal cues and the temperature range used, thermal feedback was expected to be rated as less urgent than vibration. Recognition rates for the combination of the two modalities should increase, as the same information was presented in both. As shown in previous experiments, the recognition time for thermal feedback was slow, so it was expected to be slower than the other modalities here as well. However, as there was no differences in lane deviation between modalities in the previous experiment with two tactile modalities, the same was expected here. The hypotheses for this experiment, therefore, were:

Hypothesis 1: *The bimodal stimuli will be rated as more urgent than the individual thermal and vibrotactile ones;*

Hypothesis 2: *Thermal feedback will be rated as less urgent than vibrotactile feedback;*

Hypothesis 3: *The recognition rate of bimodal notifications will be higher than vibrotactile;*

Hypothesis 4: *The recognition time will be longer for thermal feedback.*

In order to investigate those hypotheses, subjective urgency ratings, recognition rate, recognition time, lane deviation and subjective data were evaluated as dependent variables. More details can be found in Section 5.2.5 *Measures*.

5.2.2 Apparatus

For this experiment, two 1x1cm USB Peltier devices (Figure 5.1(a)), were attached to a Logitech G920 Driving Force Racing Wheel with elastic bands, one on each side. They were

(a) Hardware: Peltier device and vibrotactile actuator

(b) Steering Wheel

Figure 5.1: Experiment 5: Hardware and Steering Wheel.

placed so that the driver holding the wheel could place the thenar regions of their palms on the Peltiers, see Figure 5.1(b). The heat-sinks were isolated with cardboard, so participants would only feel the temperature of the Peltier device. In addition, one Haptuator Mark II[1] vibrotactile actuator (Figure 5.1(a) black bar) was taped onto the heat-sinks.

The subjective rating framework was implemented in Python 2.7, the interface can be seen in Figure 5.2. The slider was moved across the scale from 0 to 100 by moving the steering

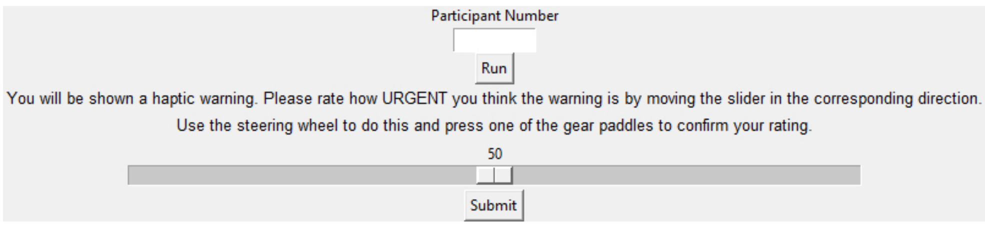


Figure 5.2: Experiment 5: Interface for Subjective Rating in Part 1.

wheel: the slider would start in the centre of the scale, steering to the left would move it to the left, steering to right to the right of the scale. The amount of steering influenced the speed of the slider movement. The range of the axis movement ranged from -1 to 1, with 0 representing the neutral starting position. An axis movement of 0.004 to the right, or -0.004 to the left, would move the slider 1 point in the desired direction. The speed increased to 3 points on the scale for an axis movement of bigger than 0.01. Pulling either of the gear

[1] http://tactilelabs.com/products/haptics/haptuator-mark-ii-v2/, accessed 31/05/2020

Figure 5.3: Experiment 5: Experimental setup.

paddles submitted the rating and triggered the presentation of the next stimulus.
The simulator environment was again implemented in OpenDS 3.5 free version and depicted a five-lane motorway with bridges (Figure 5.4). The RSeat RS1 gaming racing chair was re-used in this experiment, as was the BENQ DLP projector and the Sennheiser HD 25 Basic Edition headphones, playing driving noises during driving and white noise, generated with Audacity[2], during the first part. The equipment was run on a Dell XPS Windows laptop with Windows 10. The complete setup can be seen in Figure 5.3.

5.2.3 Driving Task and Feedback

The experiment was split into two parts. In Part 1, participants were asked to subjectively rate the perceived urgency of the feedback on a scale from 0 to 100. They were presented with a scale (see Figure 5.2) and could move the pointer by turning the steering wheel to the left or right. Their rating was submitted by pulling either gear paddle. The feedback was not introduced prior to the rating; participants were just told to expect the five different modalities. After each rating submission, the next feedback started randomly within 3s, and participants were asked to rate *0* if they had not felt anything after 5s. This was introduced to allow for missed stimuli and to ensure the experiment would go on. Each stimulus was presented three times in randomised order. Participants could take a break by not submitting their rating until they felt ready to go on. They were listening to white noise throughout this part of the experiment.
In Part 2 of the experiment, participants were asked to identify the correct stimuli during driving with a constant speed of 100km/h and report them by pressing corresponding but-

[2]https://www.audacityteam.org/, accessed 08/06/2020

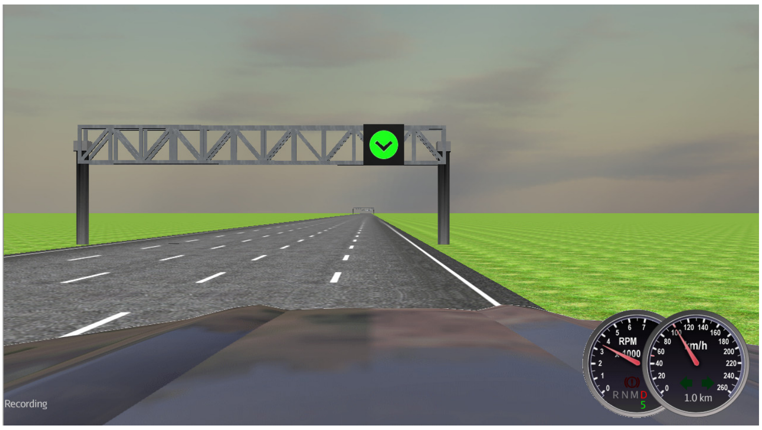
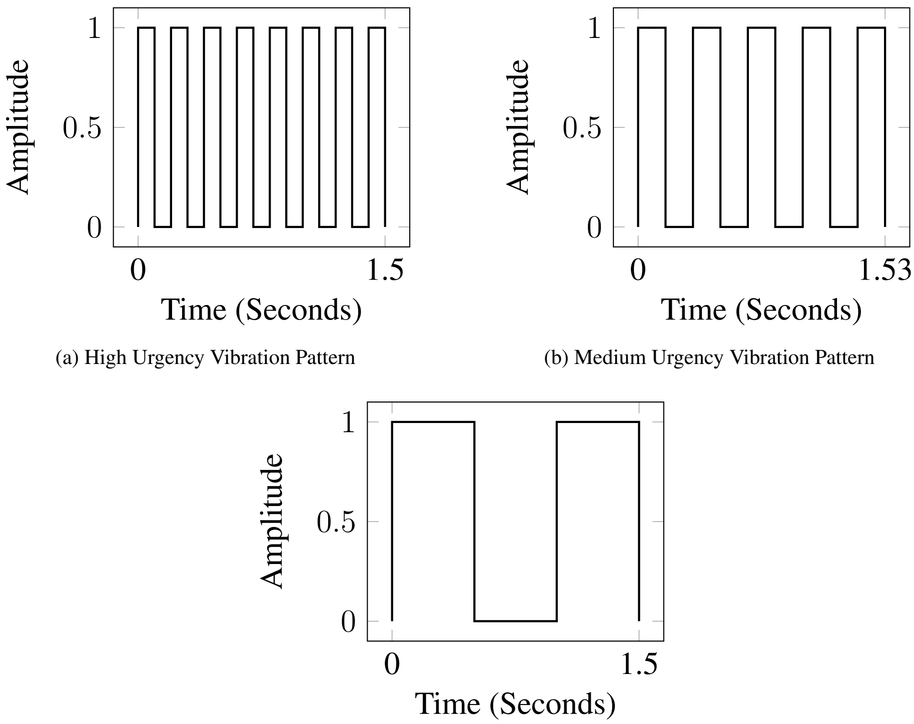


Figure 5.4: Experiment 5: Simulator Environment, arrow on gantry indicating the destination lane of the desired lane change.

tons on the steering wheel. To do this, all stimuli were first presented to them twice, making sure that they could feel each cue. They were asked to report the level of urgency: the high urgency by pressing the highest button on the steering wheel (*Y*, see Figure 5.1(b)), medium urgency by pressing the middle button (*B*) and low urgency by pressing the lowest button (*A*). To keep participants engaged with the driving, they were prompted to change lanes. Arrows would appear on gantries placed over the five-lane motorway, see Figure 5.4, indicating the lane the car should change into. The participants were encouraged to change into these lanes before arriving at the signs. The destination lanes were selected randomly. Between the lane changes, one stimulus was presented, randomly within a time frame of 3s. The lane changes and feedback cues did not overlap. Before starting the main driving task, participants fulfilled a short training drive, in which three lane changes occurred, presenting three representative stimuli: UrgentBimodalCold, MediumThermalWarm, LowVibration. During the main driving task, each feedback cue was presented three times in randomised order, leading to 45 cues in total. The driving part was broken up into driving blocks with nine cues each. Breaks could be taken in between the driving blocks.
The vibrotactile feedback was matched to the cues tested by Politis *et al.* [26], see Figure 5.5.

The sound files used for the vibration were generated with 250Hz using Audacity. The patterns encoded levels or urgency with differing number and lengths of vibrations within approximately 1.5s. The high urgency pattern had eight short vibrations of 0.1s with 0.1s intervals, see Figure 5.5(a), medium urgency was represented by five 0.17s vibration with 0.17s intervals, resulting in an overall cue time of 1.53s, see Figure 5.5(b). The low urgency only had two vibrations of 0.5s with an interval of also 0.5s, see Figure 5.5(c).

The thermal feedback was designed to match this time frame. The highest round number temperature change achievable with the hardware used within 1.5s was 4°C. This was used for high urgency rather than 4.5°C, to ensure that the temperature would be constant for some



(a) High Urgency Vibration Pattern

(b) Medium Urgency Vibration Pattern

(c) Low Urgency Vibration Pattern

Figure 5.5: Experiment 5: Vibration patterns.

time, as this was shown to be more easily recognised in Experiment 2. The medium and low urgency temperature changes were 2°C and 1°C, respectively. As the high urgency warning would always be the most important one, it was decided that the temperature change between high and medium should be more detectable. The low urgency, represented by 1°C temperature change, would be very subtle and potentially hard to detect, it was therefore important to make sure that participants had the possibility to report missed stimuli in the first part of the experiment. It was of interest to see how well these subtle cues could be identified.
The temperature changed with 3°C/s from the neutral temperature of 30°C and the temperature was then kept constant until the vibration was finished after 1.5s. At which point the temperature returned to neutral with 1°C/s. The thermal feedback can be seen in Figure 5.6: full line for high urgency, dashed line for medium urgency and dotted line for low urgency.

5.2.4 Participants and Procedure

Eighteen participants completed the experiment, no sensory impairments in their hands were reported and they had at least corrected vision. All participants obtained valid driving licences, fourteen in left-side driving countries. All but two participants were right-handed. Their data can be found in Table 5.1, with prior experience captured on a 5-point Likert scale (1 equalled no experience).

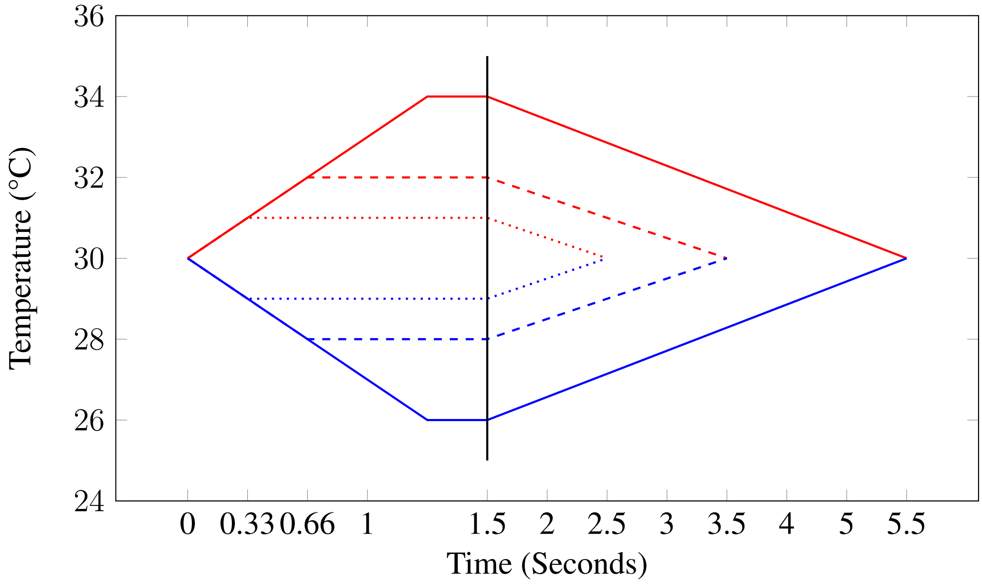


Figure 5.6: Experiment 5: Thermal feedback.

Number of Participants	Age (Years)	Driving Experience (Years)	Experience Simulator	Experience Vibration	Experience Thermal
18 (Female: 10 Male: 8)	*R*: 19-48 *M* = 27.56 *SD* = 7.59	*R*: 0-30 *M* = 8.89 *SD* = 7.47	*R*: 1-5 *M* = 2.28 *SD* = 1.07	*R*: 1-5 *M* = 1.94 *SD* = 1.06	*R*: 1-4 *M* = 1.58 *SD* = 0.86

Table 5.1: Experiment 5: Participant data, showing range (*R*), mean (*M*) and standard deviation (*SD*).

The participants were recruited through email lists and university advertisement services, being mostly university staff and students. On arrival at the university lab at the School of Computing Science, the participants were given the information sheet and then asked to sign the consent form. They were then seated in the racing chair and started the first part of the experiment, the subjective rating. After this, all stimuli were introduced to the participants and they had time to explore the driving part in the training session. This was followed by the driving task, consisting of five driving blocks interrupted by short breaks. At the end of the study participants filled in a questionnaire. The experiment lasted approximately one hour and £6 were offered as compensation.

All documents, including the questionnaire, can be found in Appendix A.6. The experiment design was approved by the Ethics Committee of the College of Science and Engineering of the University of Glasgow.

5.2.5 Measures

In this experiment participants were presented with stimuli outside of the driving task and without prior introduction. They were rating the subjective urgency on a scale of 0 to 100, with instructions to rate *0* when they could not feel anything within 5s.
Recognition rates for the correct urgency recognition during the driving task were counted and evaluated. Participants reported the identified urgency by pressing corresponding buttons on the steering wheel.
Recognition time reports the time frame from the start of the cue until the button on the steering wheel was pressed.

As in previous experiments, the lane deviation was calculated using the Root Mean Square Error for the x-position of the car compared to the middle of the occupied lane. The deviation was calculated for three time frames: *Before* the cue, starting at the bridge that defined the end of the lane change task until the beginning of the stimulus, *During* the 1.5s of the stimulus presentation and *After* the stimulus representation, starting when the cue finished and ending right before the next lane change. The time frame labelled *After* included the time in which the temperature of the thermal device returned to neutral.

Subjective data summarised answers captured in the questionnaire at the end of the experiment. Participants were asked to rank the modalities and give reasons for their ranking in free text and to choose which modality felt most urgent and most comfortable. For these questions, the modalities have been congregated and presented as *thermal*, *vibrotactile*, *bimodal (thermal and vibrotactile together)* and *all equally*. The ranking assigned numbers to the modalities, according to participants' preference: 1 being their most favourite and 3 their least favourite. The sums of these rankings therefore assign the lowest number to the most preferred modalities, while the highest number declares the least favourite.
In addition, participants could choose which direction of temperature change felt more urgent and more comfortable, presented with the options *warm*, *cold* and *both equally*. At the very end participants had the chance to leave comments in free text.

5.2.6 Results

The influence of modality and urgency were evaluated with repeated measure ANOVA, with Tukey corrections for *post hoc* tests, automatically applied in R to adjust for multiple comparisons. Outliers varying more than two standard deviations from the mean were excluded from the evaluation. Lane Deviation was evaluated with multivariate analysis of variance (MANOVA).

Subjective Urgency Ratings

In the first part of the experiment participants rated the subjective urgency of the cues without prior introduction. They were asked to rate *0*, if they did not perceive anything within 5s. However, one participant commented after the task that they rated some cues with *0*, even when they felt it, but rather found them not urgent at all.
Therefore, the *0* ratings could not be treated as missed stimuli, as intended, without additional investigation. The evaluation was made twice, once with the ratings excluded, once with them included. As the differences in the statistical results were minimal, the results of the tests for the subjective rating with the *0* ratings included were moved to Appendix A.6.4 and only the differences will be outlined here. Figure 5.7 presents subjective rating data both with and without *0* ratings. 9 Outliers were excluded for the Subjective Urgency Ratings, as they differed more than two standard deviations from the mean (1 LowBimodalWarm, 1 LowBimodalCold, 1 LowThermalWarm, 1 LowThermalCold, 1 LowVibration, 1 MediumBimodalWarm, 1 MediumThermalWarm, 1 MediumThermalCold, 1 UrgentThermalCold). The missed stimuli themselves will be evaluated as well.

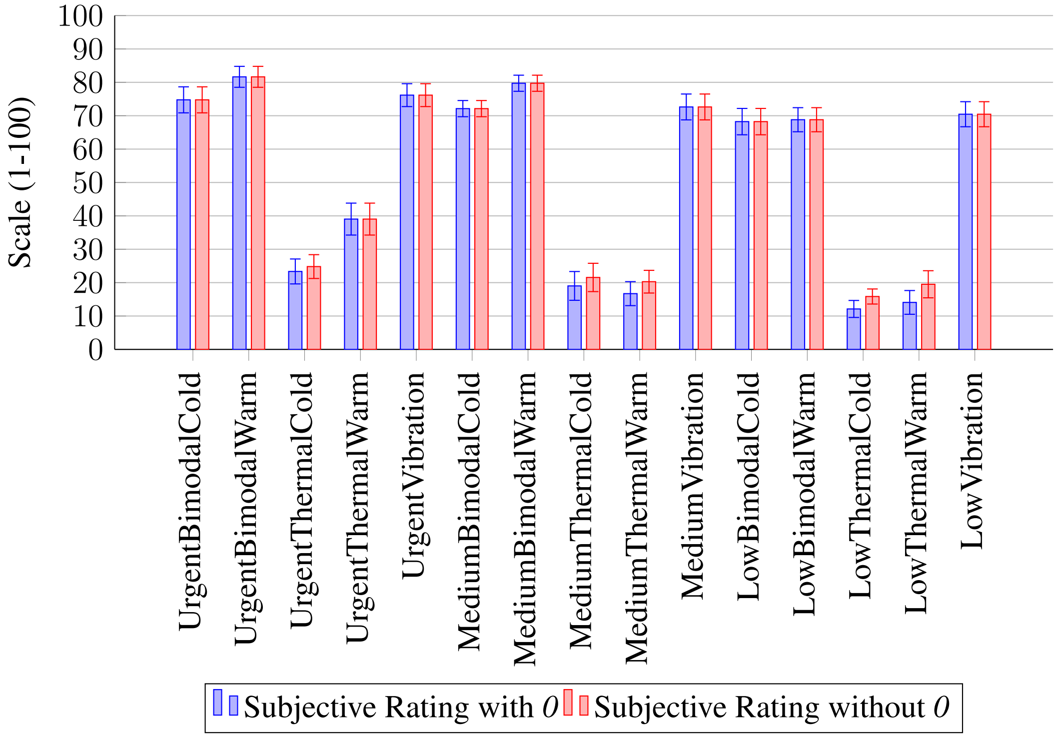


Figure 5.7: Experiment 5: Subjective Rating with and without *0* Ratings included; significant results are in bold font.

The subjective rating without *0* ratings with repeated measures ANOVA showed significant differences for Urgency ($F(2,27)$ = 21.48, $p < 0.001$), Modality ($F(4,60)$ = 112.17, $p < 0.001$) and the interaction of the two factors ($F(8,116)$ = 3.34, p = 0.002). *Post hoc* tests with Tukey corrections for Urgency showed significant differences between low - urgent (*t(34)* = 5.40, *p* = < 0.0001) and medium - urgent (*t(34)* = 3.22, *p* = 0.009), but not low - medium (*t(34)* = 2.06, *p* = 0.12). When including the *0* ratings (see Table A.1 in Appendix A.6.4), differences could be found between low - medium and low - urgent, but not medium - urgent. *Post hoc* tests with Tukey corrections for Modality showed significant results between thermal and the other modalities, see Table 5.2. A visual representation of results for *post hoc* tests with Tukey corrections of the interaction of the two factors as a heat map can be seen in Table 5.3 (all results in Appendix A.6.5). All thermal cues (light gray background in labels of the heat map) were significantly different from bimodal cues and vibration. Within the thermal conditions, LowThermalCold (LTC) was different from both urgent thermal cues and LowThermalWarm (LTW) and MediumThermalWarm (MTW) different from UrgentThermalWarm (UTW). The evaluation with *0* ratings included had similar results, see Appendix A.6.4: only LowThermalCold was not found to be different from UrgentThermalCold.

Modality - Modality	*t(60)*	*p*
Bimodal Cold - Bimodal Warm	1.34	0.67
Bimodal Cold - Thermal Cold	12.62	< **0.0001***
Bimodal Cold - Thermal Warm	10.86	< **0.0001***
Bimodal Cold - Vibration	0.65	0.97
Bimodal Warm - Thermal Cold	13.82	< **0.0001***
Bimodal Warm - Thermal Warm	12.03	< **0.0001***
Bimodal Warm - Vibration	0.69	0.96
Thermal Cold - Thermal Warm	1.67	0.46
Thermal Cold - Vibration	13.23	< **0.0001***
Thermal Warm - Vibration	11.63	< **0.0001***

Table 5.2: Experiment 5: Statistics of *post hoc* test results for Modality for Subjective Ratings without *0* ratings; significant results are bold and marked with an asterisk.

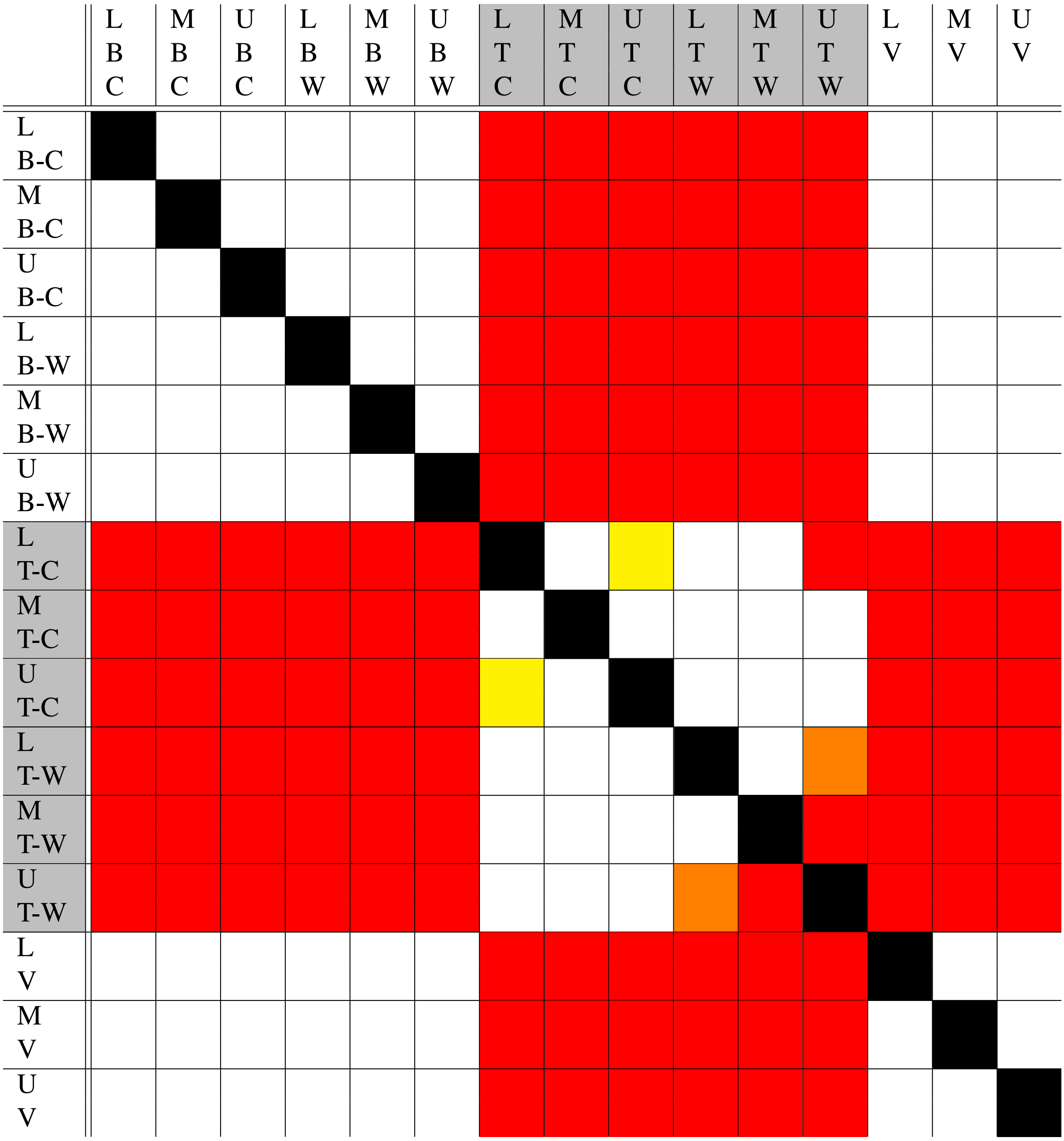


Table 5.3: Experiment 5: Heat Map of *post hoc* tests for the Interaction between Urgency and Modality for Subjective Ratings without *0* ratings included, all results can be found in Appendix A.6.5; **L**ow, **M**edium and **U**rgent notifications for **B**imodal, **T**hermal, **C**old and **W**arm, and **V**ibration are coloured yellow ($p < 0.05$), orange ($p < 0.001$) and red ($p < 0.0001$).

Missed Stimuli (*0* Ratings)

Figure 5.8 shows the number of missed stimuli or *0* ratings during the Subjective Rating at the beginning of the experiment.

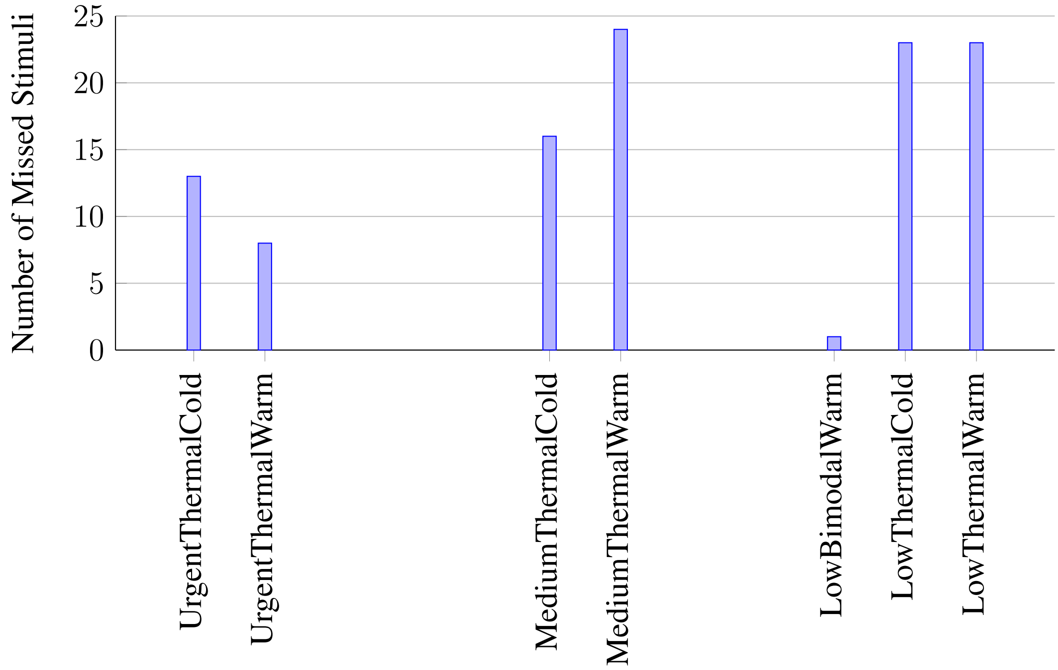


Figure 5.8: Experiment 5: Number of Missed Stimuli (*0* Ratings) during the Subjective Rating.

The evaluation with repeated measures ANOVA showed significant differences for Urgency (*F(2,34)* = 13.21, $p < 0.001$), Modality (*F(4,68)* = 20.66, $p < 0.001$) and the interaction of Urgency and Modality (*F(8,136)* = 6.01, $p < 0.001$). *Post hoc* tests with Tukey corrections for Urgency showed significant differences between low - urgent (*t(34)* = 4.97, $p = 0.0001$) and medium - urgent (*t(34)* = 3.63, $p = 0.003$), but not low - medium (*t(34)* = 1.38, $p = 0.39$). *Post hoc* tests for Modality showed significant results between the thermal conditions and the other modalities. Results of the *post hoc* tests with Tukey corrections for the interaction are represented in the heat map in Table 5.5. All results for missed stimuli can be found in Appendix A.6.6. Differences were found between all thermal medium and low cues and the bimodal and vibrotactile cues. Urgent thermal cues were an exception, where only thermal cold cues were different from the bimodal cues, except for the low bimodal warm cues. Within the thermal cues, differences were found only for the urgent thermal cues: UrgentThermalCold (UTC) was different from LowThermalCold (LTC), and UrgentThermalWarm (UTW) from LowThermalCold (LTC) and Low and MediumThermalWarm (MTW).

Modality - Modality	*t(68)*	*p*
Bimodal Cold - Bimodal Warm	0.11	1.00
Bimodal Cold - Thermal Cold	5.74	< **0.0001***
Bimodal Cold - Thermal Warm	6.07	< **0.0001***
Bimodal Cold - Vibration	0.00	1.00
Bimodal Warm - Thermal Cold	5.63	< **0.0001***
Bimodal Warm - Thermal Warm	5.96	< **0.0001***
Bimodal Warm - Vibration	0.11	1.00
Thermal Cold - Thermal Warm	0.33	1.00
Thermal Cold - Vibration	5.74	< **0.0001***
Thermal Warm - Vibration	6.07	< **0.0001***

Table 5.4: Experiment 5: Statistics of *post hoc* test results for Modality for *0* Ratings; significant results are bold and marked with an asterisk.

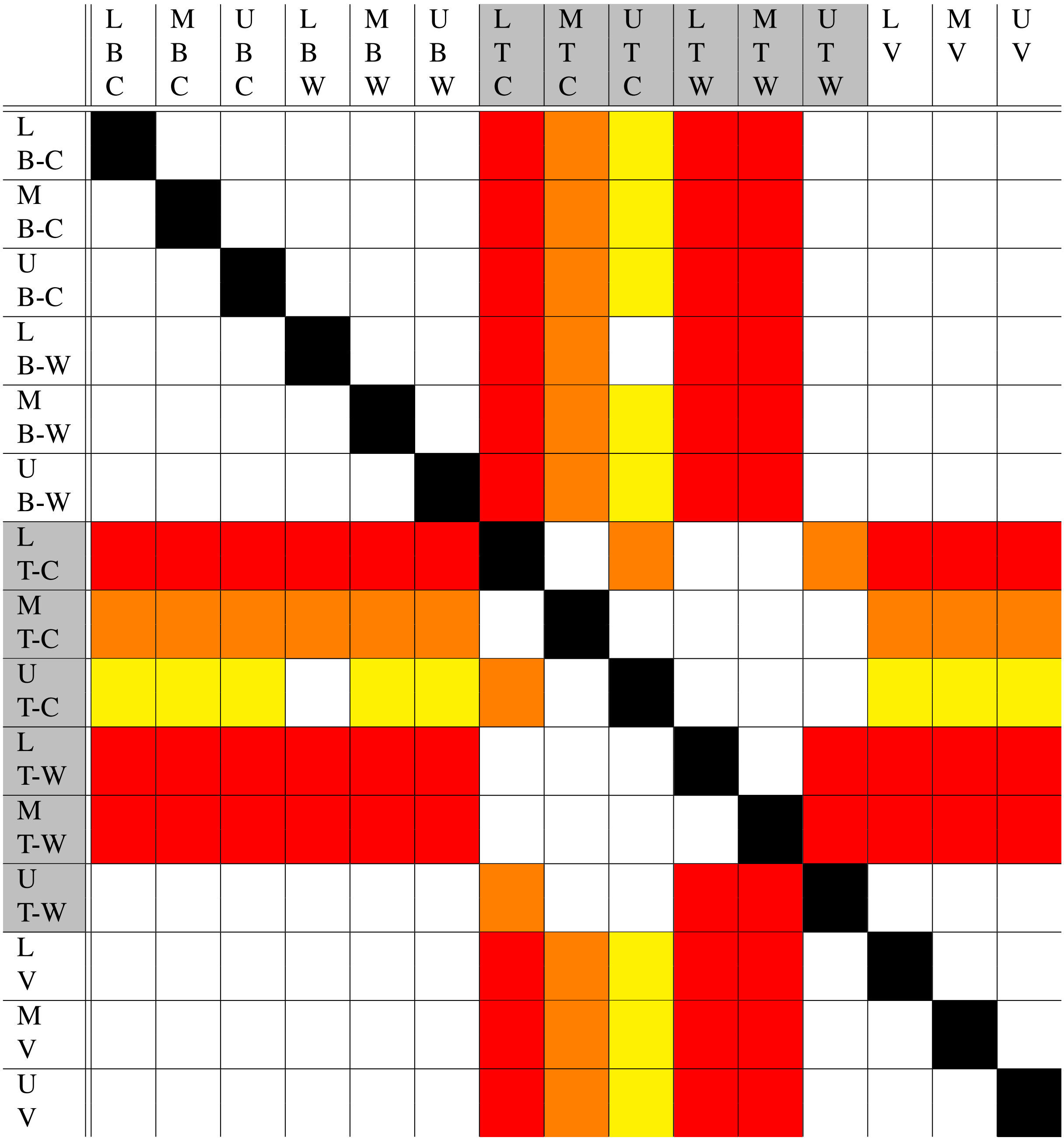


Table 5.5: Experiment 5: Heat Map of *post hoc* tests for the Interaction between Urgency and Modality for Missed Stimuli (*0* Ratings) during the Subjective Rating, all results can be found in Appendix A.6.6; **L**ow, **M**edium and **U**rgent notifications for **B**imodal, **T**hermal, **C**old and **W**arm, and **V**ibration are coloured yellow ($p < 0.05$), orange ($p < 0.001$) and red ($p < 0.0001$).

Recognition Rate

The recognition rate of the second part of the experiment can be seen in Figure 5.9. The highest recognition rate was achieved for UrgentBimodalWarm with 93%, the lowest for UrgentThermalCold with 20%. The statistical evaluation with repeated measures ANOVA

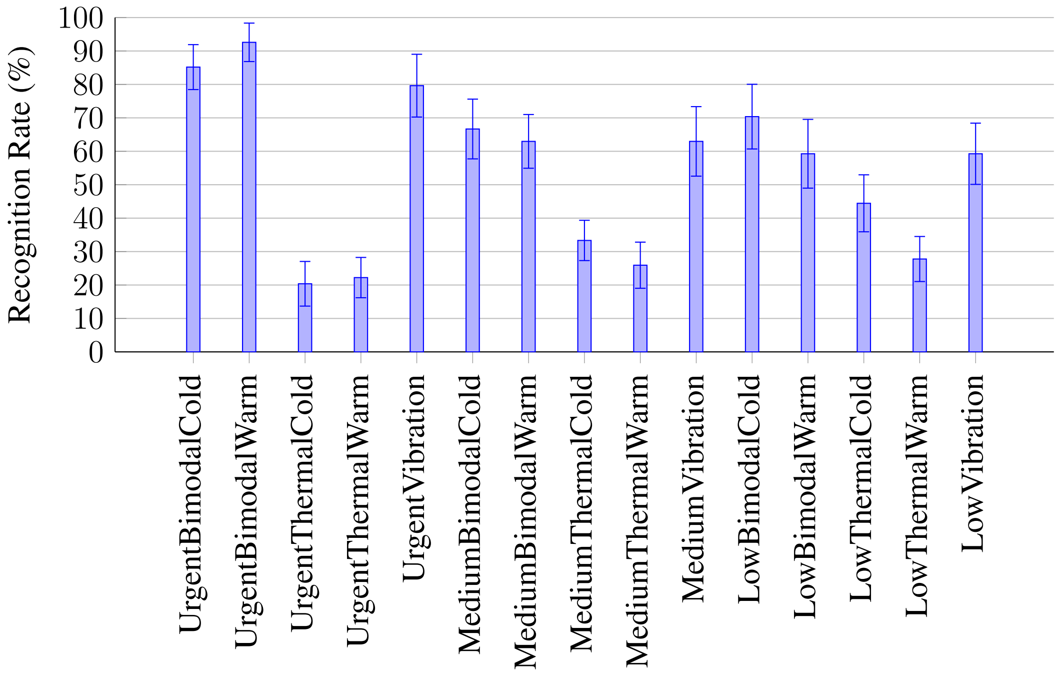


Figure 5.9: Experiment 5: Recognition Rate.

showed significant differences for Modality (*F(4,68)* = 21.41, $p < 0.0001$) and the interaction between Urgency and Modality (*F(8,136)* = 3.91, $p = 0.0004$), but not Urgency (*F(2,34)* = 2.48, $p = 0.10$).

Post hoc tests with Tukey correction for the factor Modality showed significant differences between both thermal conditions and the other cues, see Table 5.6.

Results for the *post hoc* tests with Tukey corrections of the interaction can be found as a heat map in Table 5.7, all results can be seen in Appendix A.6.7.

No differences between vibrotactile and bimodal cues was found, most significant results were in connection with thermal cues, some between bimodal cues. The urgent bimodal cold cue was significantly different from all thermal stimuli, while MediumBimodalCold (MBC) was different from all thermal warm stimuli and only the urgent thermal cold one and the low bimodal cold stimulus was different from all warm thermal stimuli and the medium and urgent bimodal cold cues. The low bimodal warm stimulus was only found to be different from both urgent thermal stimuli and the urgent bimodal warm cue. The medium bimodal warm stimulus was different from the urgent thermal stimuli and the medium warm thermal cue, while UrgentBimodalWarm (UBW) was different from all thermal stimuli. Low thermal warm and medium thermal cold were found to only be different from UrgentVibation

Modality - Modality	*t(68)*	*p*
Bimodal Cold - Bimodal Warm	0.35	1.00
Bimodal Cold - Thermal Cold	5.82	$<$ **0.0001***
Bimodal Cold - Thermal Warm	6.88	$<$ **0.0001***
Bimodal Cold - Vibration	0.964	0.87
Bimodal Warm - Thermal Cold	5.47	$<$ **0.0001***
Bimodal Warm - Thermal Warm	6.51	$<$ **0.0001***
Bimodal Warm - Vibration	0.61	0.97
Thermal Cold - Thermal Warm	1.04	0.84
Thermal Cold - Vibration	4.86	**0.0001***
Thermal Warm - Vibration	5.90	$<$ **0.0001***

Table 5.6: Experiment 5: Statistics of *post hoc* test results for Modality for Recognition Rate; significant results are bold and marked with an asterisk.

(UV), while UrgentThermalCold (UTC) was different from vibrotactile stimuli of all urgencies. Medium thermal warm stimuli were different from both medium and urgent vibration, while UrgentThermalWarm (UTW) was found to be different from vibrotactile stimuli of all urgencies. Thermal cues, especially of lower urgency, were recognised correctly less often than the other modalities.

Figure 5.10 shows the rated urgencies for each cue during the second part. In the urgent thermal modalities, the stimuli were rated more often as medium than urgent, for cold temperatures even more often low than urgent. In the medium condition, the rating for thermal almost as often medium as low, only the low thermal condition seemed to be easier to recognise correctly. The number of wrongly rated vibrotactile stimuli was higher than anticipated, especially for medium cues which were rated as urgent.

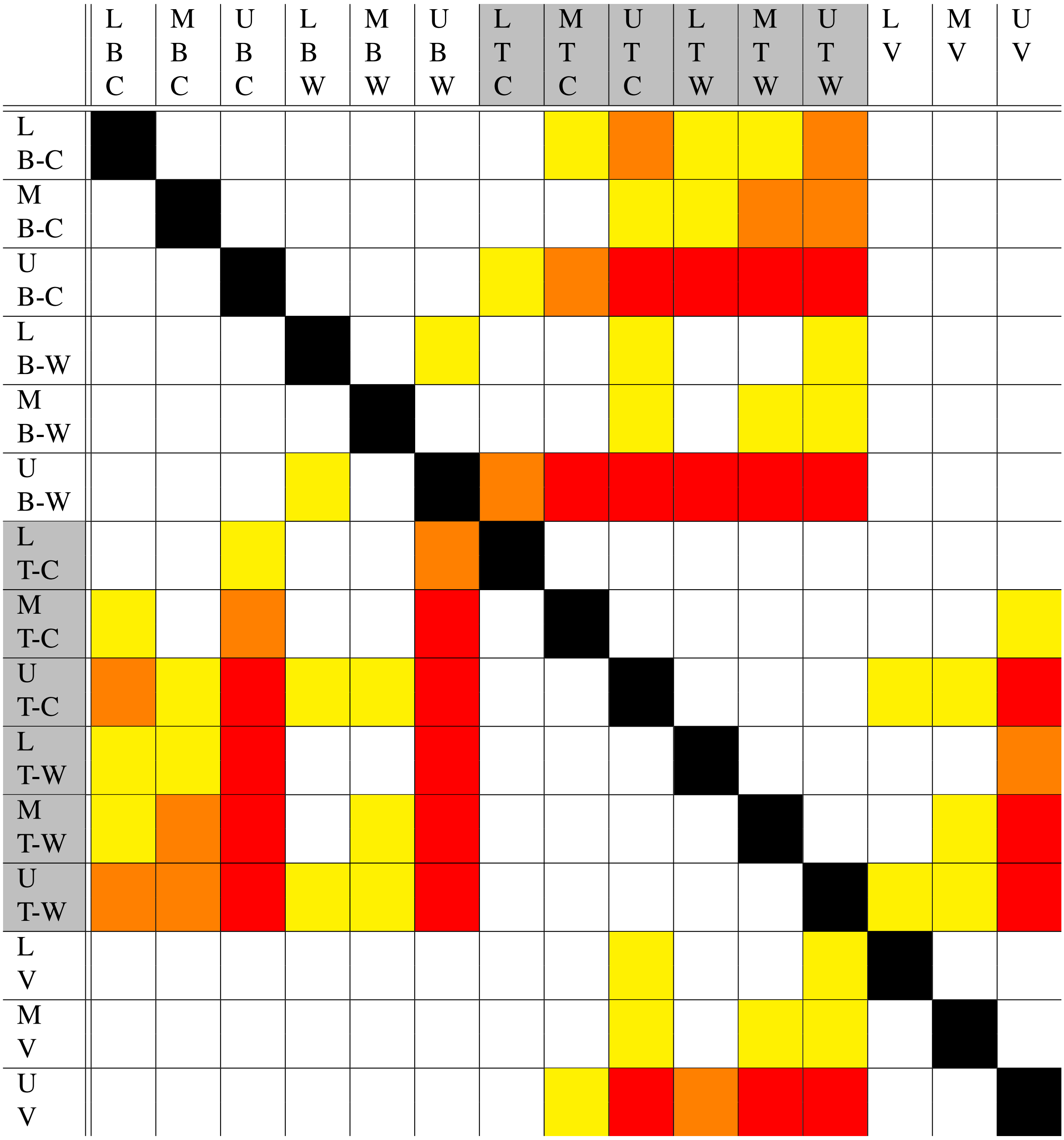


Table 5.7: Experiment 5: Heat Map of *post hoc* tests for the Interaction between Urgency and Modality for Recognition Rate, all results can be found in Appendix A.6.7; **L**ow, **M**edium and **U**rgent notifications for **B**imodal, **T**hermal, **C**old and **W**arm, and **V**ibration are coloured yellow ($p < 0.05$), orange ($p < 0.001$) and red ($p < 0.0001$).

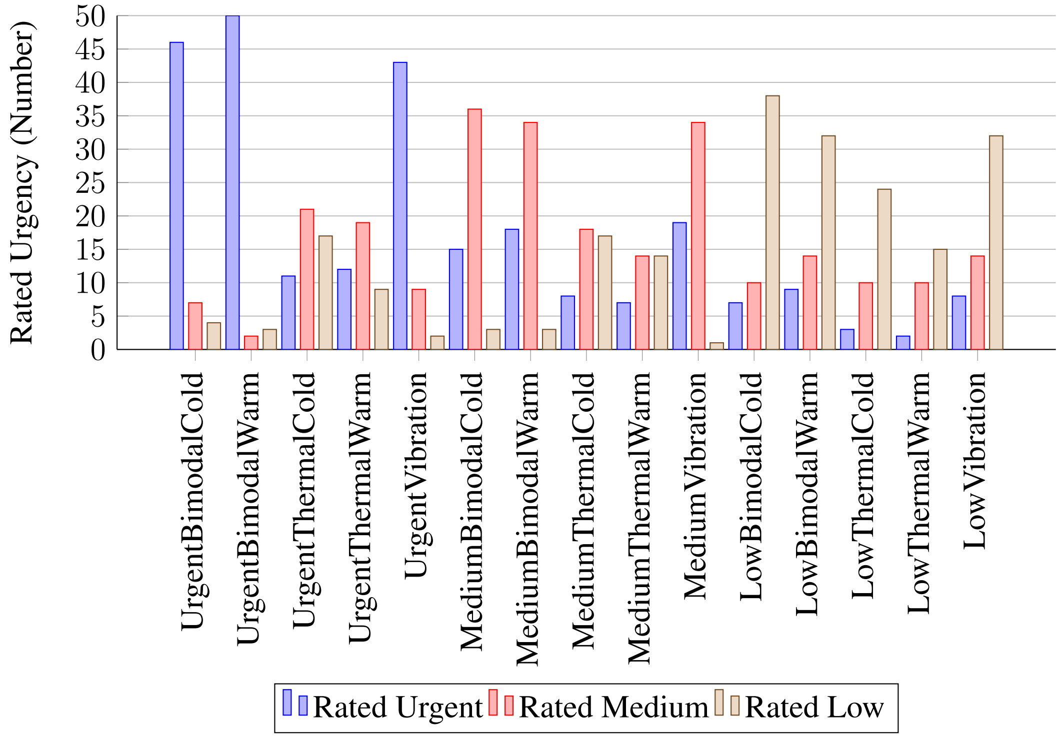


Figure 5.10: Experiment 5: Recognition: All Rating in Numbers.

Recognition Time

An overview of the recognition times can be found in Figure 5.11.

The evaluation with repeated measures ANOVA showed significant results for Modality (*F(2,28)* = 7.71 *p* = 0.0002) and the interaction of the factors (*F(4,28)* = 6.19, *p* = 0.001), but not Urgency (*F(2,28)* = 2.93, *p* = 0.07). *Post hoc* tests with Tukey corrections showed significant differences between almost all modalities, see Table 5.8. Only the differences between Bimodal Warm and Cold and between Thermal Warm and Cold were not found to

Modality - Modality	*t(63)*	*p*
Bimodal Cold - Bimodal Warm	0.15	1.00
Bimodal Cold - Thermal Cold	3.26	**0.01***
Bimodal Cold - Thermal Warm	5.02	$<$ **0.0001***
Bimodal Cold - Vibration	3.14	**0.02***
Bimodal Warm - Thermal Cold	3.40	**0.01***
Bimodal Warm - Thermal Warm	5.16	$<$ **0.0001***
Bimodal Warm - Vibration	2.99	**0.03***
Thermal Cold - Thermal Warm	1.77	0.40
Thermal Cold - Vibration	6.25	$<$ **0.0001***
Thermal Warm - Vibration	7.96	$<$ **0.0001***

Table 5.8: Experiment 5: Statistics of *post hoc* test results for Modality for Recognition Time; significant results are bold and marked with an asterisk.

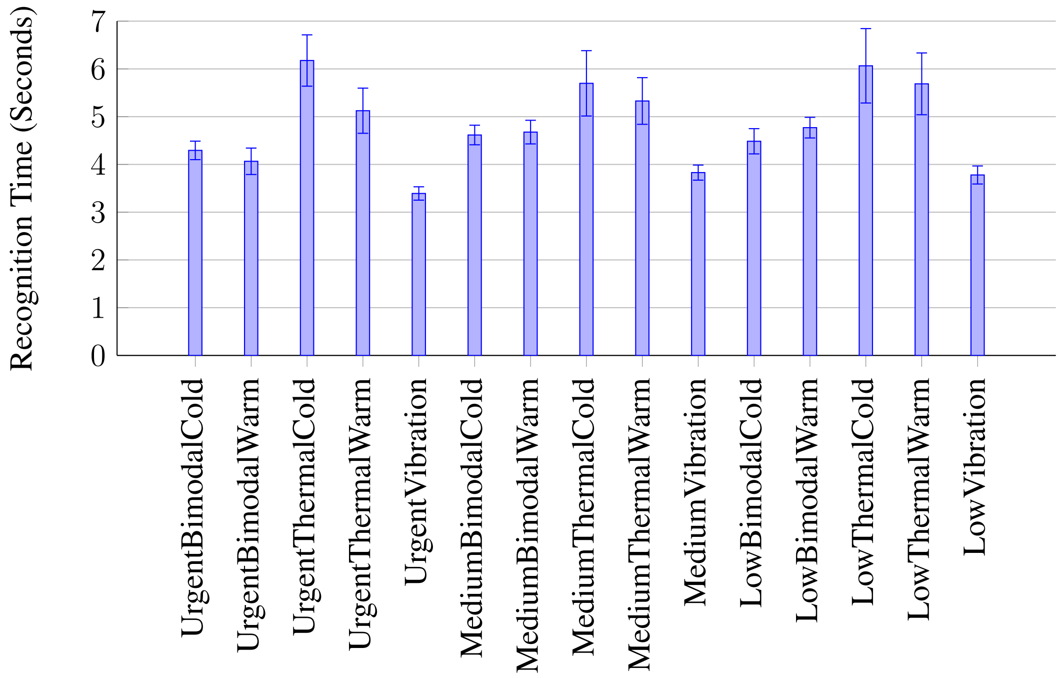


Figure 5.11: Experiment 5: Recognition Time.

be different. The thermal cues (warm: *M* = 6.01s, *SD* = 2.28; cold: *M* = 5.27s, *SD* = 32.01) took longer to be recognised than the other modalities and the bimodal modalities (warm *M* = 4.47s, *SD* = 0.81; cold: *M* = 4.50s, *SD* = 1.17) took in turn longer than vibration (*M* = 3.67, *SD* = 0.59). Significant results of *post hoc* tests with Tukey corrections for the interaction can be seen in Table 5.9 (all results in Appendix A.6.8). Low and medium bimodal cues were only different from the urgent vibrotactile stimulus. UrgentBimodalCold and Urgent-BimodalWarm were different from all thermal cues apart from UrgentThermalCold. Low and medium thermal stimuli and UrgentThermalWarm were different from all vibrotactile cues, while UrgentThermalCold was only different from UrgentVibration.

Urgency,Modality - Urgency,Modality	*t*	*p*
Low,Bimodal Cold - Urgent,Vibration	$t(196) = 4.35$	**0.002***
Medium,Bimodal Cold - Urgent,Vibration	$t(195) = 3.96$	**0.009***
Urgent,Bimodal Cold - Low,Thermal Cold	$t(194) = 4.51$	**0.001***
Urgent,Bimodal Cold - Medium,Thermal Cold	$t(193) = 4.03$	**0.007***
Urgent,Bimodal Cold - Low,Thermal Warm	$t(192) = 5.21$	<**0.0001***
Urgent,Bimodal Cold - Medium,Thermal Warm	$t(191) = 4.90$	**0.0002***
Urgent,Bimodal Cold - Urgent,Thermal Warm	$t(181) = 4.66$	**0.0006***
Low,Bimodal Warm - Urgent,Vibration	$t(196) = 3.65$	**0.03***
Medium,Bimodal Warm - Urgent,Vibration	$t(195) = 3.81$	**0.02***
Urgent,Bimodal Warm - Low,Thermal Cold	$t(194) = 3.97$	**0.009***
Urgent,Bimodal Warm - Medium,Thermal Cold	$t(193) = 3.49$	**0.04***
Urgent,Bimodal Warm - Low,Thermal Warm	$t(192) = 4.67$	**0.0005***
Urgent,Bimodal Warm - Medium,Thermal Warm	$t(191) = 4.27$	**0.002***
Urgent,Bimodal Warm - Urgent,Thermal Warm	$t(181) = 4.13$	**0.005***
Low,Thermal Cold - Low,Vibration	$t(183) = 4.12$	**0.005***
Low,Thermal Cold - Medium,Vibration	$t(194) = 4.32$	**0.002***
Low,Thermal Cold - Urgent,Vibration	$t(194) = 6.11$	<**0.0001***
Medium,Thermal Cold - Low,Vibration	$t(191) = 3.80$	**0.02***
Medium,Thermal Cold - Medium,Vibration	$t(181) = 3.75$	**0.02***
Medium,Thermal Cold - Urgent,Vibration	$t(193) = 5.64$	<**0.0001***
Urgent,Thermal Cold - Urgent,Vibration	$t(181) = 4.29$	**0.003***
Low,Thermal Warm - Low,Vibration	$t(182) = 4.81$	**0.0003***
Low,Thermal Warm - Medium,Vibration	$t(191) = 5.03$	**0.0001***
Low,Thermal Warm - Urgent,Vibration	$t(192) = 6.78$	<**0.0001***
Medium,Thermal Warm - Low,Vibration	$t(191) = 4.66$	**0.0006***
Medium,Thermal Warm - Medium,Vibration	$t(182) = 4.56$	**0.0009***
Medium,Thermal Warm - Urgent,Vibration	$t(191) = 6.49$	<**0.0001***
Urgent,Thermal Warm - Low,Vibration	$t(191) = 4.52$	**0.001***
Urgent,Thermal Warm - Medium,Vibration	$t(190) = 4.58$	**0.0008***
Urgent,Thermal Warm - Urgent,Vibration	$t(181) = 6.20$	<**0.0001***

Table 5.9: Experiment 5: Significant results of *post hoc* tests for the Interaction between Urgency and Modality for Recognition Time, all results can be found in Appendix A.6.8.

Lane Deviation

The lane deviation can be seen in Figure 5.12. Evaluation with MANOVA showed no significant differences for any factor (Urgency: $F(2,508) = 1.80$, $p = 0.10$; Modality: $F(4,765) = 0.35$, $p = 0.98$; Urgency-Modality: $F(8,765) = 1.05$, $p = 0.39$).

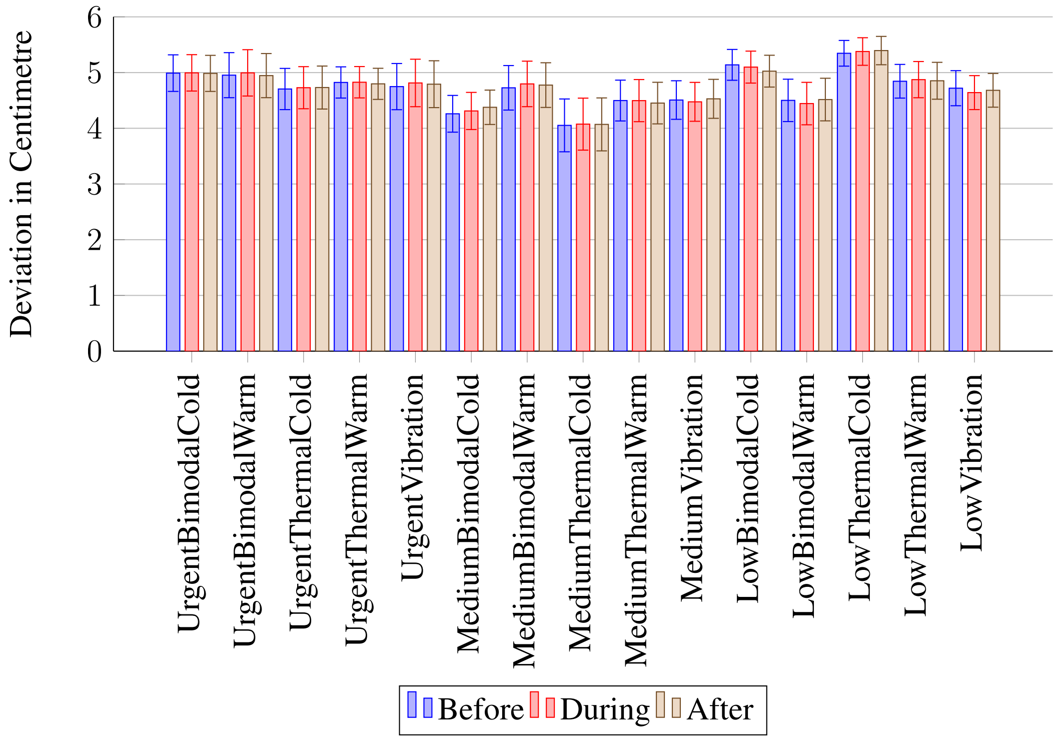


Figure 5.12: Experiment 5: Lane Deviation.

Subjective Data

At the end of the experiment participants ranked the modalities (congregated as thermal, bimodal and vibrotactile) according to their preference. Vibration achieved the lowest number in the ranking with 27, declaring it to be the most preferred modalities. It was followed closely by bimodal with 29 and thermal with 52.

Some of the reasons were named by *P10*: *Vibration was very clear. With thermal, I didn't know if it (the warmth) was the heat from my hands, the warm steering wheel or the thermal warning*. *P17* wrote that *the thermal feedback confused my senses*. The same sentiment was expressed by *P14*: *the vibrotactile feedback gave me more clear info about the urgency, while the other two ones tended to confuse me*. *P06* wrote: *I found it hard to distinguish between the intensity of the thermal rating, and also because I felt the steering wheel remained hot, it didn't have much of affect for me. The vibrations were easiest as you could count how many*, a sentiment that was shared by *P11*: *Much easier to detect and differentiate between each* *vibrotactile sensation, deeming bimodal unnecessary*. However, some participants preferred the combination of vibrotactile and thermal cues. *P07* commented: *With thermal feedback after a while you are not really feeling the temperature change especially if it is subtle. With the vibrotactile feedback I still need to think whether its urgent or not whereas the bimodal feedback gives you two feelings which I prefer (temperature change and the vibration).* And *P18* mentioned that *some of the temperature changes at lower intensities were hard to detect, vibrations were always detectable. However, when combined with vibration, the temperature changes made the overall warning feel more urgent*. *P01* wrote that *the more feedback the better - both at once makes things seem very urgent, vibrating next and lastly thermal as sometimes hard to feel*. *P05* also commented on the uncertainty of thermal feedback, as was mentioned in previous experiments: *I couldn't always feel the thermal feedback. Combination of thermal and vibration feedback did not improve it either, since I was relying primarily on the vibration feedback. I was sure I am not going to miss [it], while with thermal feedback I was always uncertain*. As for preferences of warm or cold stimuli, some participants mentioned that the cold stimuli were *uncomfortable* (*P13*) or even *a little bit painful* (*P09*), while *P04* wrote that *cold changes were better felt I think than warm*.

After the ranking participants rated which modality felt most urgent: 11 named bimodal, 6 vibrotactile and 1 thermal. However, when asked for the most comfortable modality, most participants preferred vibrotactile (10), followed by bimodal with 6. Two participants found all modalities equally comfortable. None rated thermal as most comfortable.
When asked about which direction of temperature change felt more urgent and more comfortable, more participants named warm as being more urgent (12, to 5 naming cold and 1 both equally), while they were tied for being most comfortable: 8 participants each named warm and cold, 2 found both equally comfortable.

In overall comments at the end of the experiment *P18* remarked that *it was sometimes very difficult to detect the smallest temperature changes - following a temp change of lowest intensity, I was sometimes aware that a temp change had occurred but wasn't sure whether it had gotten hotter or colder*, again pointing out a certain perceived uncertainty connected with thermal stimuli. A sentiment shared by *P10*: *just having a heated steering wheel wasn't very comfortable, and it seemed to make temperature differences less perceptible. I was never sure if I was feeling it until it got really warm, but then again - maybe it wasn't the warning after all. The vibration was a more visceral stimulus that made me more alert immediately*. *P04* pointed out the different perception of the directions of change, which was also mentioned in previous experiments: *cold more noticeable. Unsure whether warm change or from gripping steering wheel*. *P05* mentioned *thermal feedback was perceived binary and it was hard to distinguish the levels. [...] In some situations however I was paying more attention to the presence of the thermal feedback, when the vibration came. Every time the vibration came I was asking myself: is thermal feedback also here?*, suggesting that thermal and vibrotactile feedback in combination might be used in a different way.

5.2.7 Experiment 5 Discussion

This experiment was conducted to evaluate thermal and tactile bimodal feedback for three different levels of urgency. In the first part of the experiment, participants rated the perceived urgency of the stimuli on a scale from 0 to 100 without prior introduction to them. They were instructed to rate *0*, when they could not perceive any cue within 5s, but comments from a participant suggested that *0* was also used to rate thermal feedback which did not feel urgent at all. So these *0* ratings could not be used as a measure for missed stimuli without additional exploration.
The difference found by including *0* ratings was observed between thermal conditions: the low thermal cold cue was found to be different from the urgent thermal cold stimulus without the *0* ratings, but not with them included. Other differences found in both evaluations were between the thermal and the bimodal and vibrotactile modalities. Thermal cues were rated consistently as less urgent than any other modality corroborating *Hypothesis 2*. But they were also missed, or rated *0*, most often. In fact, only one non-thermal cue was missed: a low bimodal warm cue. These differences were significant. The number of misses were higher for the more subtle thermal cues, as was expected. But bimodal cues were not rated as more urgent than vibrotactile cues, so *Hypothesis 1* could not be corroborated. However, rankings and comments at the end of the experiment did suggest that most participants consider bimodal feedback to represent more urgent feedback. They also rated warm temperature changes to feel more urgent than cold ones, even though this was not mirrored in the subjective rating at the beginning.

The recognition during driving of the second part of the experiment showed an influence of the interaction between the two factors Urgency and Modality, so no easy observations can be made for the recognition rate. However, there were only differences found between thermal and bimodal cues and thermal and vibrotactile cues, even though not always of all urgencies. But there were no significant differences between bimodal and vibrotactile cues, so *Hypothesis 3* could not be corroborated. These interactions could be a result of the small difference between the low and medium thermal cues. The numbers of wrongly rated cues indicated that especially the medium thermal cues were often mistaken for low urgency ones. In addition, urgent thermal cues were rated medium and even low often, with the urgent cold cue being rated urgent less often than both other urgency levels. Participants also reported on problems differentiating the thermal cues. In addition, participants misidentified an unanticipated high number of vibrotactile cues during driving. Medium and low vibrotactile patterns were mixed up almost one third of the time, with medium often interpreted as urgent and low as medium. The chosen cue design in general seemed to not have produced easily distinguishable levels of information. Decreasing the number of levels from three to two and lengthening the time for cue presentation of the thermal feedback could aid in creating more distinct levels of information.

As in previous experiments, it can also be observed that the perception of warm and cold stimuli was not always simply mirrored. As the preferences of the two directions of change differ, so does the perception of them. As thermal preferences can differ between individuals, the feedback might have to be personalisable for practical use. In an in-car environment, this could be easily accomplished by an additional setting for each driver, which could be set once and only adapted when needed.

Evaluation of recognition time showed that thermal cues took longer to be recognised than both bimodal and vibrotactile cues, corroborating *Hypothesis 4*. It was also seen that vibrotactile feedback was recognised faster than bimodal cues. The advantage of increased reaction time of vibration found in previous research seemed to have been compromised by the addition of thermal feedback. This addition in recognition time renders bimodal feedback, and in extension thermal feedback, unsuitable for urgent notifications in a driving environment, as an increase of reaction time might have fatal consequences. However, these modalities could be very useful for non-urgent notifications. One participant mentioned that their attention towards thermal cues was heightened after feeling vibration. Combining thermal and vibrotactile cues to convey different kinds of information might benefit from the certainty participants feel towards vibration and help them recognise additional thermal feedback without the uncertainty reported with it. Recognition rates for some thermal cues have been high and could reliably present information different from the one given through vibration. The next experiment will explore this idea and present two different types of information, both unimodally with thermal alone and bimodally in combination with vibration.

5.3 Experiment 6: Uni- and Bimodal Tactile Notifications with Different Types of Information

This experiment investigated thermal and bimodal tactile cues to present information of two different types, with the bimodal cues consisting of thermal and vibrotactile feedback. The cue design is comparable to the study conducted by Wilson *et al.* [44].

5.3.1 Methodology

The study was designed as a 2x2x2 within-subjects experiment, with Modality (thermal/bimodal), Importance (high/low) and Nature (personal/work) of a message as the independent variables.

As bimodal feedback has been identified more easily in the previous experiments, it is expected to fare the same in this experiment. However, as the thermal cues were chosen from the highest performing cues from Experiment 2, the difference might not be very much pronounced. Preference ratings at the end of the experiment were, however, still expected to favour bimodal feedback, as participants have felt more assured in their senses when vibration was involved. The hypotheses for this study, therefore, were:

Hypothesis 1: *Recognition of bimodal stimuli will be higher;*

Hypothesis 2: *Preference ratings will favour the bimodal condition.*

The dependent variables used to discuss these hypotheses were recognition rate and subjective ratings. More details on these can be found in Section 5.3.5 *Measures*.

5.3.2 Apparatus

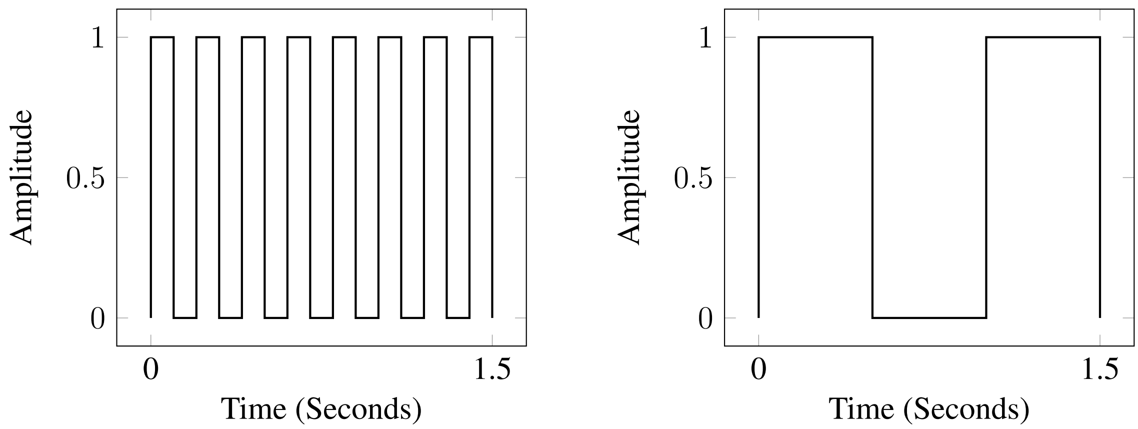
The experimental setup was similar to Experiment 5, the only difference being that large 2x2cm Peltier devices were attached to the steering wheel with sports bands, see Figure 5.13.

Figure 5.13: Experiment 6: Steering Wheel.

5.3.3 Driving Task and Feedback

The driving task adopted for this experiment was the same as in Experiment 5. Participants navigated the simulated car with a constant speed of 100km/h on a five-lane motorway and changed lanes when prompted by appearing arrows on gantries in front of them. The destination lanes were chosen randomly and participants were asked to change into the lanes before they reached the gantry. The feedback was more complex than in Experiment 5 and the used Peltier devices bigger, which made reaching the buttons on the steering wheel without moving the hands off the thermal devices unfeasible. The participants, therefore, reported the identified Importance and Nature of the feedback orally back to the experimenter, who logged them by pressing corresponding keys on the keyboard. All cues were presented 8 times, resulting in 40 cues overall. These were presented within 45 lane changes (as in Experiment 5), resulting in 5 *empty* lane changes without any feedback presented. This was adopted to ensure that participants would not feel pressured to report a cue at each lane change. The order of the presented stimuli and empty lane changes was randomised.

The feedback combined thermal stimuli from Experiment 2 and vibrotactile stimuli from Experiment 5. The thermal patterns were chosen from the cues with the highest recognition rates (over 90%) and the lowest rates for false positives (under 10%).
The factor Importance in the bimodal condition was presented by the vibrotactile pattern used in Experiment 5: the high urgency pattern for high importance (see Figure 5.14(a)) and the low urgency pattern for low importance (see Figure 5.14(b)).



(a) High Importance Vibration Pattern

(b) Low Importance Vibration Pattern

Figure 5.14: Experiment 6: High and Low Importance Vibration Patterns.

The vibration of the bimodal cues was combined with the thermal patterns *c/w-3-6-s* from Experiment 2, see Figure 5.15, dashed lines. The temperature was changed 6°C with a rate of 3°C/s, kept constant for 3s and then returned to the neutral temperature of 30°C with a rate of 1°C/s.
The direction of temperature change encoded the factor Nature: a cold temperature change was used for work messages, while a warm temperature change was used for personal messages. This mapping was chosen, because previous research showed that warm temperature increased perceived friendship and emotional stability [111] and even reminded participants

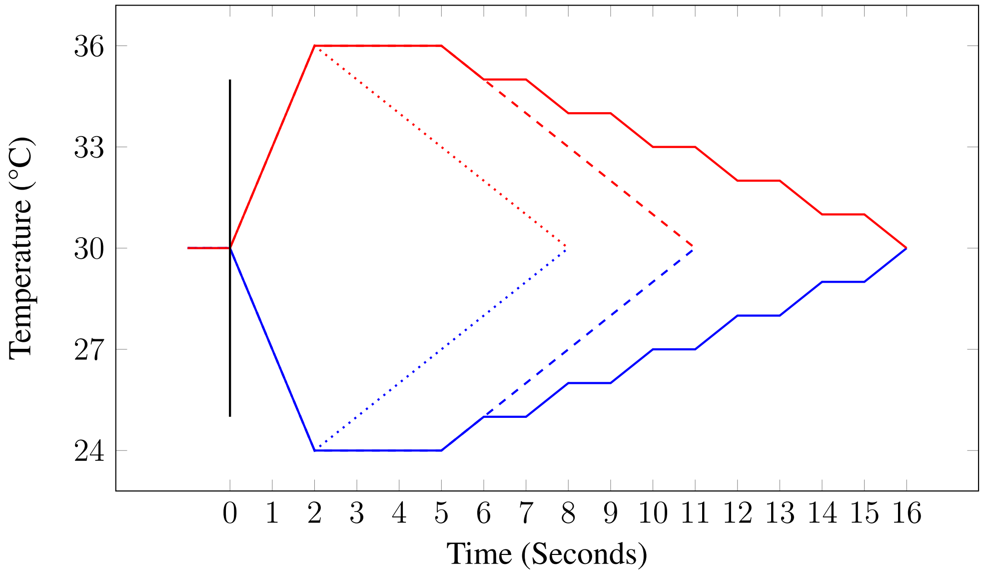


Figure 5.15: Experiment 6: Thermal feedback.

of a *loving home* [112] and it was assumed that mapping warm to home would feel more natural. The thermal feedback in the bimodal condition started once the vibration was finished. While the direction of change also depicted the Nature in the thermal condition, two different thermal patterns were used to encode the Importance of a message. Low importance messages were presented by very short thermal changes, *c/w-0-6-s*, where the temperature was changed 6°C with 3°C/s and returned to neutral with 1°C/s directly after reaching the goal temperature, see Figure 5.15, dotted lines. High importance messages were presented with the thermal pattern *c/w-3-6-a*, where the temperature was changed 6°C with 3°C/s, held at that temperature for 3s and then returned to the neutral temperature at the *angled* rate. At this rate the temperature was changed for 1°C at a rate of 1°C/s, held constant for 1s and then changed again, keeping this pattern until the temperature reached the neutral temperature of 30°C, see Figure 5.15 solid line.

5.3.4 Participants and Procedure

Eighteen newly recruited participants completed the experiment. None had sensory impairments in their hands and only corrected vision. They all had valid driving licenses, twelve obtained theirs in left-side driving countries. Table 5.10 shows more detailed participant data.

The study was advertised via email lists and using university services and therefore attracted mostly students and university employees. The study was conducted in labs within the School of Computing Science and after welcoming the participants, they were presented with an information sheet and a consent form, which they signed. While seated in the gaming racing chair, participants were introduced to the feedback, showing them all stimuli. This

Number of Participants	Age (Years)	Driving Experience (Years)	Experience Simulator	Experience Vibration	Experience Thermal
18 (Male: 8 Female: 9 Non-Binary: 1)	*R*: 18-36 $M = 25.72$ $SD = 4.93$	*R*: 0.5-18 $M = 6.33$ $SD = 4.80$	*R*: 1-3 $M = 2.00$ $SD = 0.77$	*R*: 1-5 $M = 2.77$ $SD = 1.64$	*R*: 1-3 $M = 1.56$ $SD = 0.78$

Table 5.10: Experiment 6: Participant data, showing range (*R*), mean (*M*) and standard deviation (*SD*).

was followed by a training session before the main driving task started, which was broken up in five blocks of driving with short breaks in between. At the end of the experiment, participants filled in the questionnaire and were compensated with a £10 Amazon voucher for taking part in the one hour study.

The documents for this experiment can be found in Appendix A.7. The experimental design was approved by the College Ethics Committee.

5.3.5 Measures

The most important dependent variable in this experiment was recognition rate. The recognition of the two factors Nature and Importance will be investigated independently and together.

The recognised cue was reported orally to the experimenter and then recorded by them, so the recognition time could not be evaluated because of the occurring delay.

Lane Deviation was calculated in the same way as in Experiment 5.

Subjective data and ratings were collected at the end of the experiment, including a ranking of how well the stimuli could be identified, as well as how much they liked the modalities and how easy they could differentiate the thermal and vibrotactile patterns, each on a 5-point Likert scale.

5.3.6 Results

The influence of the three independent variables was evaluated with repeated measures ANOVA. *Post hoc* tests were done with Tukey corrections, automatically applied in R to adjust for multiple comparisons. Lane Deviation was calculated with MANOVA. The subjective data were evaluated with Friedman's ANOVA, with Wilcoxon pairwise comparisons as *post hoc* tests, or Wilcoxon for comparison of only two factors.

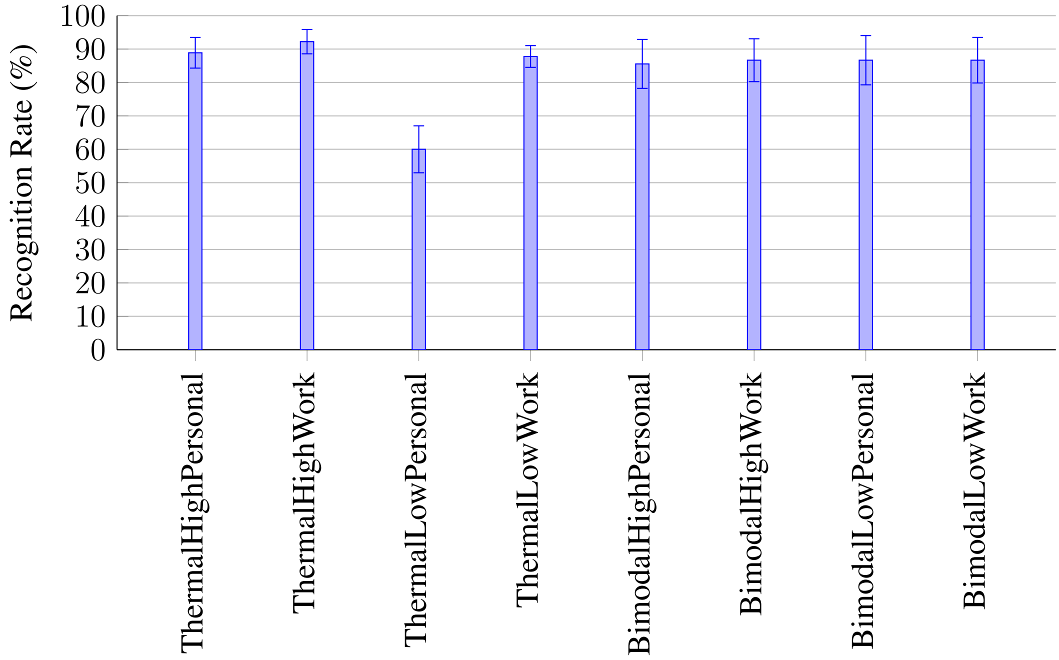


Figure 5.16: Experiment 6: Recognition Rate.

Recognition Rate

The recognition rates for all stimuli can be seen in Figure 5.16. The cue with the lowest recognition was ThermalLowPersonal, the short warm thermal stimulus, with a recognition rate of 60% (single factors: Nature 64%, Importance 63%). The highest recognition was achieved for ThermalHighWork, the long cold thermal cue, with a recognition rate of 92% (single factors: Nature 94%, Importance 93%). All other thermal cues were recognised correctly between 88% and 89%, the bimodal cues between 86% and 87%. Recognition of single factors over thermal stimuli (excluding ThermalLowPersonal) was between 91% and 96% for Nature and 88% and 93% for Importance and for bimodal cues between 97% and 99% for Nature and 86% and 88% for Importance. There was no significant difference found with repeated measures ANOVA for factor Modality, but all other factors and interactions, see Table 5.11.

High important notifications (M = 288.33, SD = 23.31) were better recognised than low im-

Modality	Importance	Nature	Modality: Importance	Modality: Nature	Importance: Nature	Modality: Importance: Nature
$F(1,17)$ = 0.44 p = 0.51	$F(1,17)$ = 17.94 **p < 0.001***	$F(1,17)$ = 6.60 **p = 0.02***	$F(1,17)$ = 18.3 **p < 0.001***	$F(1,17)$ = 7.61 **p = 0.01***	$F(1,17)$ = 15.72 **p = 0.001***	$F(1,17)$ = 8.67 **p = 0.009***

Table 5.11: Experiment 6: Statistics for Recognition Rate; significant results are bold and marked with an asterisk.

portant notifications (*M* = 256.11, *SD* = 25.95) and work notifications (*M* = 288.33, *SD* = 21.35) better than personal ones (*M* = 256.11, *SD* = 27.91).

Modality:Importance	*t*	*p*
BimodalHigh - ThermalHigh	*t(20.5)*=0.67	0.36
BimodalHigh - BimodalLow	*t(33.9)*=0.20	1.00
BimodalHigh - ThermalLow	*t(20.1)*=1.87	0.27
ThermalHigh - BimodalLow	*t(20.1)*=0.60	0.93
ThermalHigh - ThermalLow	*t(33.9)*=6.02	$<$ **0.001***
BimodalLow - ThermalLow	*t(20.5)*=1.95	0.24

Table 5.12: Experiment 6: Statistics of *post hoc* test results of Recognition Rate for the interaction between Modality and Importance; significant results are bold and marked with an asterisk.

The *post hoc* tests with Tukey corrections for the interaction for Modality and Importance can be seen in Table 5.12. The only significant result was found between thermal of high and low importance, where ThermalHigh (*M* = 135.00, *SD* = 17.45) had a better recognition than ThemalLow (*M* = 103.89, *SD* = 21.82).

Modality:Nature	*t*	*p*
BimodalPersonal - ThermalPersonal	*t(23.2)*=1.71	0.34
BimodalPersonal - BimodalWork	*t(33.3)*=0.13	1.00
BimodalPersonal - ThermalWork	*t(25.0)*=0.56	0.94
ThermalPersonal - BimodalWork	*t(25.0)*=1.75	0.32
ThermalPersonal - ThermalWork	*t(33.3)*=3.75	**0.004***
BimodalWork - ThermalWork	*t(23.2)*=0.49	0.96

Table 5.13: Experiment 6: Statistics of *post hoc* test results of Recognition Rate for the interaction between Modality and Nature; significant results are bold and marked with an asterisk.

The *post hoc* tests with Tukey corrections for the interaction between Modality and Nature can be seen in Table 5.13 and only showed significant differences between ThermalPersonal (*M* = 104.44, *SD* = 24.65) and ThermalWork (*M* = 136.11, *SD* = 14.63), where work were recognised better than personal notifications. The *post hoc* tests with Tukey corrections for the interaction between Importance and Nature can be seen in Table 5.14. There were significant differences between high and low personal notifications, where HighPersonal (*M* = 131.67, *SD* = 25.28) was recognised better than LowPersonal (*M* = 103.33, *SD* = 30.54), between LowPersonal and HighWork (*M* = 135.56, *SD* = 21.33), with the former was recognised worse than the latter and between low personal and work notifications, where LowWork (*M* = 131.11, *SD* = 21.37) was recognised better than LowPersonal. The *post hoc* tests with Tukey corrections for the interaction between all three factors shows significant differences between ThermalLowPersonal and all other stimuli, but no other cues (Table 5.15).

Importance:Nature	*t*	*p*
HighPersonal - LowPersonal	*t(32.0)*=5.78	< **0.001***
HighPersonal -HighWork	*t(24.1)*=0.64	0.92
HighPersonal - LowWork	*t(28.0)*=0.00	1.00
LowPersonal - HighWork	*t(28.0)*=4.39	**0.001***
LowPersonal - LowWork	*t(24.1)*=4.01	**0.003***
HighWork - LowWork	*t(32.0)*=0.92	0.79

Table 5.14: Experiment 6: Statistics of *post hoc* test results of Recognition Rate for the interaction between Importance and Nature; significant results are bold and marked with an asterisk.

Modality:Importance:Nature	*t*	*p*
BimodalHighPersonal - ThermalHighPersonal	*t(32.0)*=0.45	1.00
BimodalHighPersonal - BimodalLowPersonal	*t(63.8)*=0.29	1.00
BimodalHighPersonal - ThermalLowPersonal	*t(29.0)*=3.53	**0.03***
BimodalHighPersonal - BimodalHighWork	*t(55.4)*=0.23	1.00
BimodalHighPersonal - ThermalHighWork	*t(31.4)*=0.90	0.98
BimodalHighPersonal - BimodalLowWork	*t(58.3)*=0.22	1.00
BimodalHighPersonal - ThermalLowWork	*t(33.6)*=0.29	1.00
ThermalHighPersonal - BimodalLowPersonal	*t(29.0)*=0.31	1.00
ThermalHighPersonal - ThermalLowPersonal	*t(63.8)*=7.58	< **0.001***
ThermalHighPersonal - BimodalHighWork	*t(31.4)*=0.30	1.00
ThermalHighPersonal - ThermalHighWork	*t(55.4)*=0.68	1.00
ThermalHighPersonal - BimodalLowWork	*t(33.6)*=0.29	1.00
ThermalHighPersonal - ThermalLowWork	*t(58.3)*=0.22	1.00
BimodalLowPersonal - ThermalLowPersonal	*t(32.0)*= 3.59	**0.02***
BimodalLowPersonal - BimodalHighWork	*t(58.3)*=0.00	1.00
BimodalLowPersonal - ThermalHighWork	*t(33.6)*=0.73	1.00
BimodalLowPersonal - BimodalLowWork	*t(55.4)*=0.00	1.00
BimodalLowPersonal - ThermalLowWork	*t(31.4)*=0.15	1.00
ThermalLowPersonal - BimodalHighWork	*t(33.6)*=3.53	**0.02***
ThermalLowPersonal - ThermalHighWork	*t(58.3)*=6.46	< **0.001***
ThermalLowPersonal - BimodalLowWork	*t(31.4)*=3.59	**0.02***
ThermalLowPersonal - ThermalLowWork	*t(55.4)*=5.66	< **0.001***
BimodalHighWork - ThermalHighWork	*t(32.0)*=0.75	1.00
BimodalHighWork - BimodalLowWork	*t(63.8)*=0.00	1.00
BimodalHighWork - ThermalLowWork	*t(29.0)*=0.15	1.00
ThermalHighWork - BimodalLowWork	*t(29.0)*=0.77	1.00
ThermalHighWork - ThermalLowWork	*t(63.8)*=1.17	0.94
BimodalLowWork - ThermalLowWork	*t(32.0)*=0.15	1.00

Table 5.15: Experiment 6: Statistics of *post hoc* test results of Recognition Rate for the interaction between Modality, Importance and Nature; significant results are bold and marked with an asterisk.

Lane Deviation

The evaluation of the lane deviation with MANOVA (see Figure 5.17) showed no significant differences for any factor or time frame, see Table 5.16.

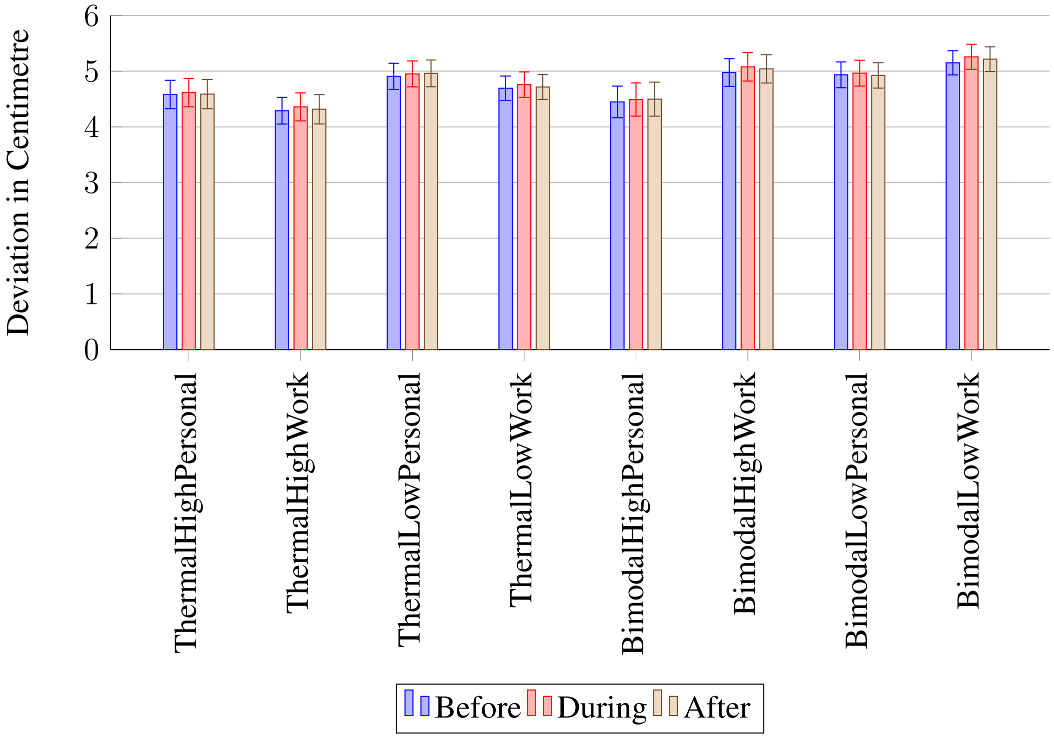


Figure 5.17: Experiment 6: Lane Deviation.

Modality	Importance	Nature	Modality: Importance	Modality: Nature	Importance: Nature	Importance: Modality: Nature
$F(3,134) = 0.87$ $p = 0.46$	$F(3,134) = 1.57$ $p = 0.20$	$F(3,134) = 2.14$ $p = 0.10$	$F(3,134) = 0.86$ $p = 0.46$	$F(3,134) = 1.34$ $p = 0.26$	$F(3,134) = 0.05$ $p = 0.98$	$F(3,134) = 1.07$ $p = 0.36$

Table 5.16: Experiment 6: Statistics for Lane Deviation; significant results are bold and marked with an asterisk.

Subjective Data

All subjective ratings can be seen in Figure 5.18. Participants' rating of how much they liked the two modalities was compared with Wilcoxon and showed significant differences ($V = 0$, $p < 0.001$). Bimodal feedback (*median* = 5) was liked more than thermal feedback (*median* = 3).

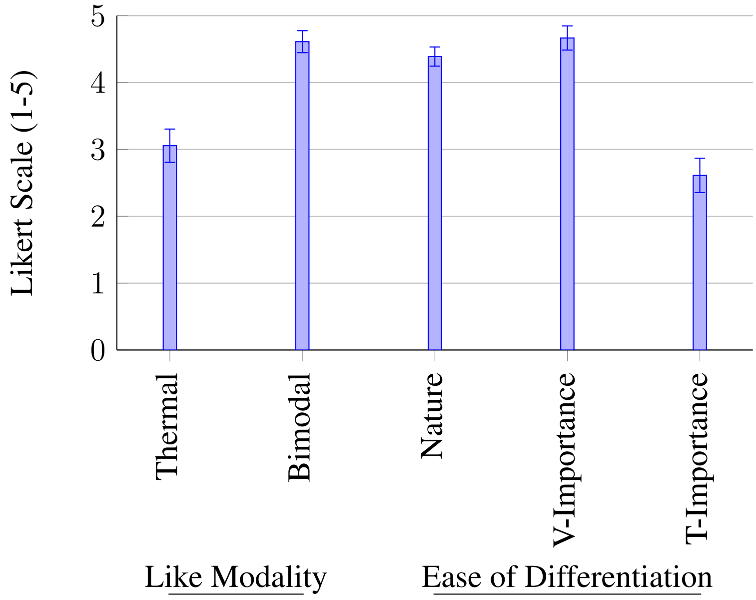


Figure 5.18: Experiment 6: All Subjective Ratings.

The ratings of how easily the direction of temperature change (Nature), the lengths of temperature change (T-Importance) and vibration patterns (V-Importance) were evaluated with Friedman's ANOVA, showing significant differences ($\chi^2(2)$ = 27.74, $p < 0.001$). *Post hoc* tests with Tukey corrections showed significant differences for Nature - T-Importance (V = 120, p = 0.001) and T-Importance - V-Importance (V = 0, $p < 0.001$), but not Nature - V-Importance (V = 8, p = 0.16). T-Importance (*median* = 3) was differentiated with more difficulty than both Nature (*median* = 4) and V-Importance (*median* = 5).

The ranking of the stimuli at the end of the experiment can be seen in Figure 5.19, with numbers showing how often each stimulus was sorted into at a specific rank, with *Rank 1* being the highest rank and, therefore, the stimulus deemed best to identify by participants. The bimodal stimuli were more often ranked into the top positions, with the high importance vibration pattern preferred, while thermal feedback was more often ranked towards the bottom. Also, notifications for personal messages were ranked higher than work messages, showing a preference for warm stimuli.

P07 summarised this in their comment *Longer vibrations easier to feel and heat easier to feel than cold*, as did *P08*: *Found the bimodal stimuli much clearer - less likely to think I had received a message when I hadn't*. This highlights the uncertainty around thermal feedback that was already addressed in previous experiments, picked up as well by *P06*: *Although I could differentiate between all of the bimodal ones, sometimes I wondered whether the thermal ones were just my hands being over-sensitive / getting used to the temperature. P11* commented *thermal feedback only can be hard to distinguish, especially the low importance ones as it can be confused for normal hand temperature fluctuation. Bimodal made this eas-*

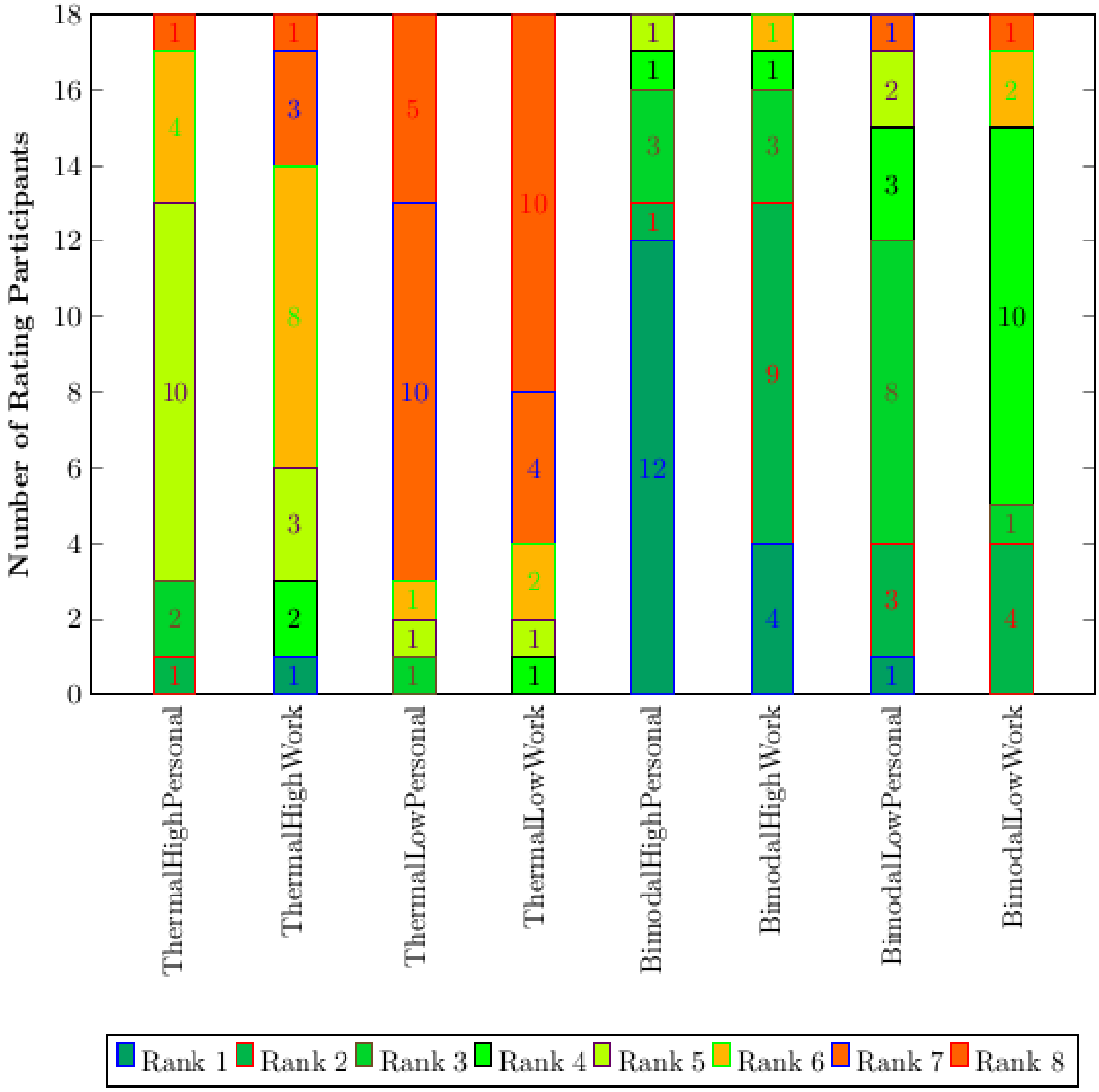


Figure 5.19: Experiment 6: Ranking of Stimuli.

ier as you can expect a change in temperature. P05 wrote *I found it much easier to identify the bimodal prompts. I struggled to differentiate between the lengths of time of the thermal prompts*

The combination of vibration and temperature changes was commented on favourably overall: *The vibration was more clear than thermal and also feeling it let me know I should now expect thermal which took away the worry of missing the thermal* (*P01*); *the bimodal gave a clear indication that there was a notification, and gave a cue to keep an eye for the thermal changes to see what type of notification it was* (*P02*); *Bimodal was easier to identify because it raises your attention with the vibrations and then informs you whether the message was private or work-related. Thermal only could not be identified at times* (*P04*).

Participants noted on the time it took to identify the stimuli. While *P12* wrote that *the vibrations were always obvious and you could tell their meaning instantaneously, unlike the thermal ones where you had to wait till they had ended to be sure and also sometimes it could be hard to detect the low importance thermal ones*, *P16* shared that they *felt that it was easier to quickly identify the form of stimulus from just the thermal ones, since the timing and heat sensation were provided together. Although it was sometimes difficult to quickly determine the length of the thermal stimuli, which is why having the vibration made it easier. P11* mentioned that *the temp change in bimodal should start at the same time as the vibrations so that it doesn't take so long to get info about the notification*.

Another observation made in the previous experiments was affirmed in the comments as well: preferences for warm and cold stimuli differ throughout the participants. *P02* noted that they *had a bit more trouble identifying the cold change than the hot one*, requiring more focus. *P08* commented that they *found the hot sensation clearer than the cold. P01*, on the other hand, noted that they *found cold easier to feel than hot* and *P16* concurs that *the cold thermal feeling was easier to identify than the warm one. P03* mentioned that they *could identify the work and home stimuli equally as well*.

There were a few comments on the vibration patterns. *P11* noted: *The vibration pattern for low importance seems more urgent than high importance to me. The high importance one is just like a normal phone notification. P17* wrote about the low importance vibration pattern that *the style of vibration can be confusing, like it still feels important (like an alarm).* They suggested that the pattern should be changed.

5.3.7 Experiment 6 Discussion

In this experiment thermal and vibrotactile cues were combined to present two types of information on the steering wheel. The cues were chosen from previous experiments and combined to present either unimodal thermal or bimodal tactile notifications about the Nature and Importance of a message. The evaluation showed that all factors apart from Modality

had an influence on the recognition, including interactions between the different factors. A closer look showed that ThermalLowPersonal stimuli, the short warm thermal cues, were recognised significantly worse than any other stimulus. This finding was mirrored in the interactions with the aggregated factors. The recognition rate of this cue was with 60% the lowest by far, with almost all other cues having recognition rates between 86% and 89%, with ThermalHighWork, the long cold thermal cue, being the only one above this with 92%. Bimodal cues had slightly smaller recognition rates than thermal cues. Factor Nature had very high recognition, higher than Importance for both thermal and vibration patterns. Direction of temperature was especially well recognised after a vibration in the bimodal feedback. In Experiment 2, ThermalLowPersonal, there labelled *w-0-6-s*, had a recognition rate of 94%. This substantial drop in recognition was surprising. The cues in Experiment 2 were presented on one Peltier device of the same size, with a finger tip touching the device. In this experiment, the temperature was presented on both hands and on the thenar region, which is usually more susceptible to tactile feedback. If anything, this setup should have led to an increase in recognition. The driving task in this experiment was slightly more challenging than in Experiment 2, as the lane change prompts in this study were presented visually and not haptically. This could have led to an increase in cognitive load of the driving task and influenced the recognition of the presented cues. In addition, the presentation on the hands gripping the wheel might have increased the feeling of warmness emanating naturally from the hands instead of the devices.
Hypothesis 1 claimed that the recognition for bimodal stimuli would be higher, which could not be corroborated. Participants ranked the stimuli according to their ease of identification and consistently ranked bimodal cues higher than thermal cues, only one participant ranked ThermalHighWork as the cue that could be identified the best, yet the recognition rate would suggest that this stimulus was most easily distinguished. In the ranking, this cue, however, was most often rated on Rank 6, after all bimodal cues and ThermalHighPersonal. The stimulus with the lowest recognition rate, ThermalLowPersonal, was also not found most often in the last spot, as would be expected, but on Rank 7, before ThermalLowWork. Some participants commented, as in previous experiments, how they were not sure sometimes if the warming of the steering wheel was a cue or due to the hands getting warm, yet the short warm stimulus was still ranked higher than the cold one. Preferences of direction of temperature change differed between participants.

Hypothesis 2 could be corroborated: participants very clearly rated that they preferred the bimodal to the unimodal thermal condition. Comments suggested that participants appreciated the certainty presented by the vibration and could use it to concentrate on the following temperature change. Some participants mentioned that the vibration patterns did not convey the intended level of importance to them. This issue could be overcome in practical applications by allowing to personalise vibration patterns. There was, however, no confusion mentioned on the mapping of direction of temperature change for Nature of message: warm for personal and cold for work messages. This could mean that this association was familiar enough to be easily remembered, while the vibration patterns were more generic. Utilising inherent associations of temperature changes could increase recognition of cues immensely.

Experiment 5 and 6 investigated unimodal thermal and bimodal thermal and vibrotactile feedback for notifications. In the next experiment, bimodal haptic feedback will be investigated in combination with the non-tactile modalities audio and visual, and in a more applied context.

5.4 Experiment 7: Multimodal Feedback for Transfer of Control in Semi-Autonomous Cars

In this experiment bimodal thermal and vibrotactile feedback was added to a pre-tested set of multimodal cues for transfer of control. The tactile feedback was used to inform on the status of control transfer, rather than inform on obstacles or danger on the road. The autonomous feature was a level 3 system, Traffic Jam Pilot, much like the traffic jam chauffeur mentioned in 2.3.2. It took over full control of the car in a traffic jam situation on the motorway, when the speed was slower than 40mph. Drivers were required to be available to take over control when needed. In this experiment only handover and driver-initiated takeover were investigated.

5.4.1 Methodology

The study was designed as 2x2 within-subjects experiment, with Haptic (on/off) and Visual (on/off) as the independent variables. Not all combinations were tested, the version without haptic and visual feedback was skipped. Haptic feedback was bimodal with thermal and vibrotactile feedback, while visual feedback described a visual progress bar behind the steering wheel on the instrument cluster, which was either visible or not. The observed conditions were:

- Visual progress bar, without haptics (**NoHapVis**)
- Visual progress bar, with haptics (**HapVis**)
- No visual progress bar, with haptics (**HapNoVis**)

The transfer of control was triggered by the simultaneous pulling of the gear paddles on the steering wheel. Pilot tests showed that participants took a long time to take their hands of the steering wheel and their foot off the accelerator pedal after the handover of control to the car. The use of haptic feedback was expected to shorten this time as vibrotactile cues would remind the driver that their manual control was no longer needed and reaffirm the successful control transfer, potentially leading to safer driving during the transfer and increased trust in and preference of the system. Thermal feedback informed on the progress of the control transfer, much like the visual progress bar. It was of interest to see if the tactile presentation would render the visual feedback unnecessary, which could lead to less eyes-off-the-road time and as a consequence to safer driving.

An additional condition **Buttons** was added, to compare if the use of the gear paddles would have benefits over triggering the control transfer by simultaneously pressing two buttons on the steering wheel, which was used in pilot tests. The feedback for this condition was similar to the condition NoHapVis and was only compared directly to this condition. In pilot tests utilising the button press to transfer the control, participants were taking their eyes off the road for long glances in order to find the correct buttons on the steering wheel. It was hypothesised that the use of the gear paddles would reduce this. The hypotheses for this experiment, therefore, were:

Hypothesis 1: *Haptic feedback will lead to faster disengagement with the steering wheel and accelerator pedal after handover;*

Hypothesis 2: *Haptic feedback will positively influence driving behaviour and increase trust in the system;*

Hypothesis 3: *Participants will prefer the conditions with additional haptic feedback;*

Hypothesis 4: *The lack of visual feedback will lead to less eyes-off-the-road time;*

Hypothesis 5: *Transferring control with buttons will lead to longer eyes-off-road time and more long glances away from the road.*

The dependent variables used to investigate these questions were: time to disengage with the steering wheel and accelerator pedal, lane deviation and number of micromotions of the steering wheel, eyes-off-the-road time and number of long glances away from the road, subjective ratings after each condition and a ranking at the end of the experiment. More detailed information on the dependent variables can be found in Section 5.4.5 *Measures*.

5.4.2 Apparatus

The hardware used for the tactile feedback were the 2x2cm Peltier devices and the Haptuators Mark II vibrotactile actuators used in previous experiments. One vibrotactile actuator was taped onto the heat-sink of each Peltiers. The top side of the heat-sinks were insulated with cork, so fingers would only feel the temperature of the thermal device. The device was

(a) Hardware (b) Setup

Figure 5.20: Experiment 7: Hardware and experimental setup.

taped onto a copper sheet, which was in turn attached to the gear paddle with Velcro tape, see Figure 5.20(a). An additional vibrotactile actuator was placed under the accelerator pedal.
The study was conducted in a high-fidelity driving simulator setup, see Figure 5.20(b), at the Jaguar Land Rover Driving Lab at the University of Warwick. The high-fidelity simulator environment was made available by Jaguar Land Rover for the experiment as part of an internship, and full details of the system cannot be provided.
The simulator environment was implemented using STI Sim[3] software, with the driving scenario being presented on a large screen in front of the driving cabin. The driving environment can be seen in Figure 5.21. Additional small screens were integrated into the setup as instrument cluster, centre console and side windows. Three webcams were filming the driver, each focusing on a different region of interest. One camera was pointed at the face of the driver to capture gaze data, one filmed the feet and their pedal use and one pointed at the hands to capture their interaction with the steering wheel. Video logs captured the input of those cameras as well as the output of the instrument cluster, centre console and side windows.

[3]https://stisimdrive.com/, accessed 01/06/2020

Figure 5.21: Experiment 7: Driving simulator environment as captured in the video log. The side mirror content was presented to drivers on screens at the side of the driving cabin.

5.4.3 Driving Task and Feedback

The driving task in this experiment was the same for all conditions. The drive started with the car being placed on the left shoulder of a three lane motorway. Participants were asked to move the car to, and stay within, the middle lane, driving with a constant speed of around 40mph. After approximately 1.5min the traffic intensified, forcing the driver to slow down. When the speed of the car moved under 40mph, the autonomous feature became available. The feature was activated by pulling both gear paddles (or two buttons on the steering wheel in condition Buttons) for 2s. When the control was transferred to the car, 2min video snippets of movies (*Up*[4], *Skyfall*[5], *The Hunger Games*[6] and *Frozen*[7]) were automatically played on the centre console without prompting. The order of the videos was counterbalanced over the conditions. When the videos stopped, the experimenter asked the participants to take back control from the car the same way they handed it over. They then drove manually for approximately 2min, after which they were asked to move the car back to the left shoulder of the motorway and stop the car.

Visual and audio feedback was provided in all conditions. When the autonomous feature

[4]Up (2009), https://www.imdb.com/title/tt1049413/
[5]Skyfall (2012), https://www.imdb.com/title/tt1074638/
[6]The Hunger Games (2012), https://www.imdb.com/title/tt1392170/
[7]Frozen (2013), https://www.imdb.com/title/tt2294629/

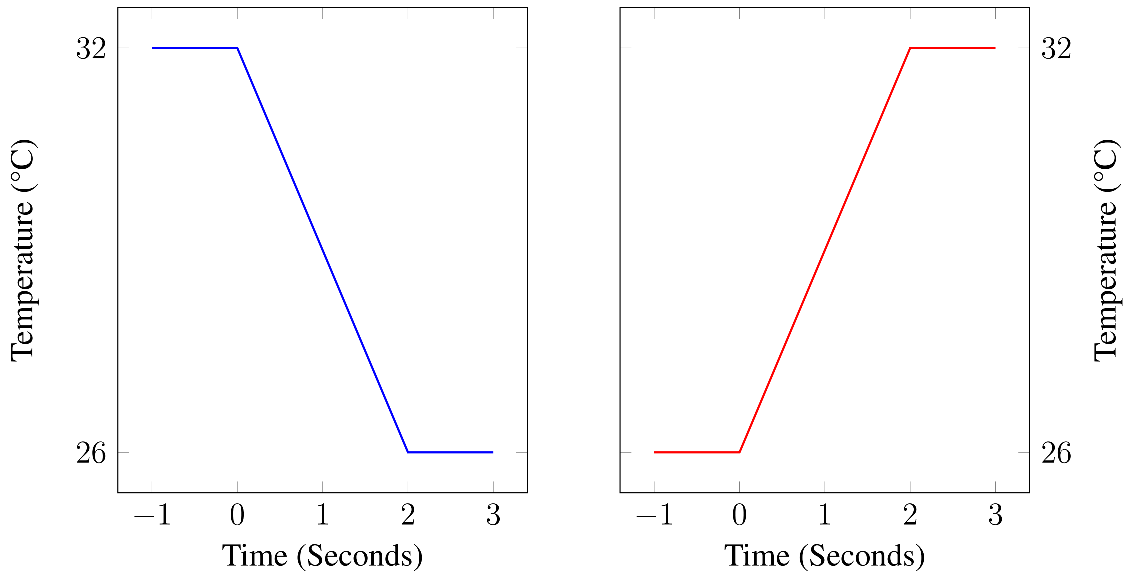


Figure 5.22: Experiment 7: Thermal feedback: Handover (left) and Takeover (right).

became available, a (proprietary) visual icon appeared on the instrument cluster, accompanied by a non-vocal sound notification (*ding*). When the driver started the control transfer by pulling the gear paddles (or pressing the buttons), the progress was presented by showing a visual progress bar in the instrument cluster behind the steering wheel, in the Visual-On conditions (HapVis and NoHapVis/Buttons). The haptic feedback presented in the Haptic-On conditions (HapVis and HapNoVis) consisted of thermal feedback and vibrotactile feedback. The thermal devices were set to 32°C during manual driving and changed during the handover to 26°C with 3°C/s, see Figure 5.22 left. When the control was transferred, the vibrotactile actuators on the gear paddles and the accelerator pedal vibrated for 0.5s. The process during takeover was similar, only the temperature changed from 26°C back to 32°C, see Figure 5.22 right. The warmer temperature was chosen for manual driving, as previous research has linked warm temperatures to activity and presence [113], which corresponds with manual rather than automated driving. The completion of the transfer process was accompanied by speech feedback in all conditions, uttering *Traffic Jam Pilot activated* after handover and *Traffic Jam Pilot deactivated* after takeover. In addition, the instrument cluster changed its appearance from presenting the classical round speedometer design to a (proprietary) presentation of the car in its surroundings[8].

The order of the conditions was counterbalanced over the participant pool and the order of movie snippets was counterbalanced over conditions.

[8]Comparable to the Tesla design, https://teslatap.com/wp-content/uploads/2015/10/TeslaTap_instrument_v7_p85d_720.jpg, accessed 14/08/2020

5.4.4 Participants and Procedure

Fourteen participants, all employees of Jaguar Land Rover with valid UK driving licenses, completed the study. Their job descriptions ranged from market researchers, to patent attorneys to training developers and human factors specialists. All but one were right-handed, the last one named both right and left as dominant hands, see Table 5.17 for more detailed demographic data.

Number of Participants	Age (Years)	Driving Experience (Years)	Experience Autonomous	Experience Simulator	Experience Vibration	Experience Thermal
14 (Female: 3 Male 11)	*R*: 24-58 *M* = 38.21 *SD* = 12.98	*R*: 3-41 *M* = 18.43 *SD* = 12.33	*R*: 1-5 *M* = 3.14 *SD* = 1.46	*R*: 1-5 *M* = 2.50 *SD* = 1.51	*R*: 1-5 *M* = 3.36 *SD* = 1.36	*R*: 1-2 *M* = 1.43 *SD* = 0.51

Table 5.17: Experiment 7: Participant data, showing range (*R*), mean (*M*) and standard deviation (*SD*).

The participants were recruited via internal organisation mails. The study was conducted at Jaguar Land Rover labs located at the University of Warwick in Coventry. Participants were welcomed and presented with an information sheet, before they were asked to sign a consent form. They were then guided to the high fidelity driving simulator and seated. Participants were given a chance to get used to the simulator with a 2min drive without any feedback. This was followed by an introduction of the first feedback and the corresponding driving part, after which participants were asked to fill in a questionnaire. This was repeated for the remaining feedback types. At the end of the experiment, participants filled in an additional questionnaire, capturing demographic data and subjective ratings. The experiment took approximately one hour, participants were not compensated for their time.

For all documents, please refer to Appendix A.8. This experiment was approved both by the College Ethics Committee of the University of Glasgow as well as the internal Jaguar Land Rover Ethics procedures.

5.4.5 Measures

The evaluation of the video data provided some of the dependent variables. The videos were manually labelled and the time data extracted to discern how long participants took to let go off the steering wheel (HandsOff) and the accelerator pedal (FootOff) and to return the foot after takeover (FootOn). Additionally, the gaze behaviour was extracted from the videos, labelling the time frames participants averted their gaze from the forward road from the moment the autonomous feature became available until the control had been fully handed over to the car (CompleteHandover) and from the start of the takeover process until the driver was driving fully manual (CompleteTakeover). There were several areas of interest that the gaze would turn to: down to the steering wheel, to the instrument cluster behind the steering wheel just under the front window, upwards towards the rear mirror or left/right to the two mirrors on the side. Overall eyes-off-the-road (Eyes-Off-Road) time was calculated as the sum of these. Any glances longer than 2s during the handover process were counted as well, as these long glances have been shown to be major contributor to crashes and should be avoided. Long glances and eyes-off-the-road time during the takeover process were ignored, as the car was still driving autonomously and glances away from the road, therefore, posed no danger.

The lane deviation was extracted from the driving log provided by the driving simulator and was calculated, as before, using the RSME to summarise the driving behaviour again for the time the autonomous feature became available until the control was fully transferred. Driving behaviour was compared both between conditions, evaluating the influence of the independent variables, and within conditions, comparing the baseline driving with the driving during the handover process. The baseline of the same length as the handover process was captured just before the feature was available, to allow for a close comparison. While the data for the user initiated takeover process was captured as well, it could not be compared to the baseline, as the road conditions had changed noticeably during the autonomous drive. A baseline right before the takeover would have only captured the cars' driving behaviour and a baseline right after takeover might have unduly been influenced by the driver settling back into driving and adjusting the cars trajectory to the personally preferred position within the lane. Driving behaviour, therefore, was only investigated for the handover process.

The driving simulator log captured changes in driving rather than capturing a screenshot of the data at specific time intervals. This provided additional information on the driving behaviour: the number of micromotions used to achieve the presented level of lane deviation. Every new move of the steering wheel prompted a new entry into the log, therefore, many such movements could indicate fidgeting which in turn indicates anxiety, uncertainty or distraction from the driving. A low number of micromotions were interpreted as positive.

After the driving task of each condition, participants filled in questionnaires capturing perceived workload, with the NASA TLX questionnaire, as well as the four additional ratings from previous experiments (pleasantness, comfort, complexity and disruptiveness) on a 10-point Likert scale. Additionally, an open-text comment section was available.

Another questionnaire was presented at the end of the experiment, capturing a ranking of all four conditions, as well as a rating of how well the thermal feedback could be felt with and without the visual progress bar (on a 10-point Likert scale). Additionally, participants indicated whether the condition influenced their trust in the system and were then asked to rate their trust for each condition on a 10-point Likert scale. A free text comment section was also provided.

5.4.6 Results

The evaluation of the data was done with repeated measures ANOVA for gaze data, driving behaviour between conditions and subjective ratings. *Post hoc* tests were done with Tukey corrections, automatically calculated in R to adjust for multiple comparisons. Outliers of more than two standard deviations have been excluded for these statistical evaluations. Condition *Buttons* will be included in the figures, but will only be evaluated in section 5.4.6. The comparisons of driving within conditions and between Buttons and NoHapVis were done with t-tests (*t(df)*), when the data were normally distributed, or Wilcoxon tests (V) otherwise.

Time Observations

The timings extracted for the video logs can be seen in Figure 5.23. For the gaze evaluation there were outliers for Eyes-Off-Road (1 HapNoVis, 1 NoHapVis), CompleteHandover (1 NoHapVis), HandsOff (1 HapNoVis), FootOff (1 NoHapVis), CompleteTakeover (2 HapVis) and FootOn (1 NoHapVis, 1 HapNoVis), were the values differed more than two standard deviations from the mean. The results of the statistical evaluation with repeated measures ANOVA, see Table 5.18, showed significant differences for FootOff for Visual, where participants took longer for Visual-Off (M = 1.13, SD = 0.50) than Visual-On (M = 1.01, SD = 0.70). Additionally, FootOn showed significant differences for Haptic, where Haptic-Off was faster (M = 0.79, SD = 0.39) than Haptic-On (M = 1.22, SD = 0.71). The HandsOff outlier removed for condition HapNoVis was very much higher (141.21s) than the mean for this condition (11.21s), which can be seen in Figure 5.23.

	Eyes-Off-Road	Complete Handover	Hands Off	Foot Off	Complete Takeover	Foot On
Haptic	$F(1,11)$ = 0.90 p = 0.36	$F(1,12)$ = 1.24 p = 0.29	$F(1,12)$ = 0.57 p = 0.47	$F(1,12)$ = 4,49 p = 0.06	$F(1,12)$ = 0.40 p = 0.54	$F(1,11)$ = 6.66 **p = 0.03***
Visual	$F(1,12)$ = 2.06 p = 0.18	$F(1,13)$ = 0.00 p = 0.96	$F(1,12)$ = 0.11 p = 0.75	$F(1,13)$ = 6.51 **p = 0.02***	$F(1,11)$ = 1.53 p = 0.24	$F(1,12)$ = 2.79 p = 0.12

Table 5.18: Experiment 7: Statistics for Time Observations; significant results are bold and marked with an asterisk.

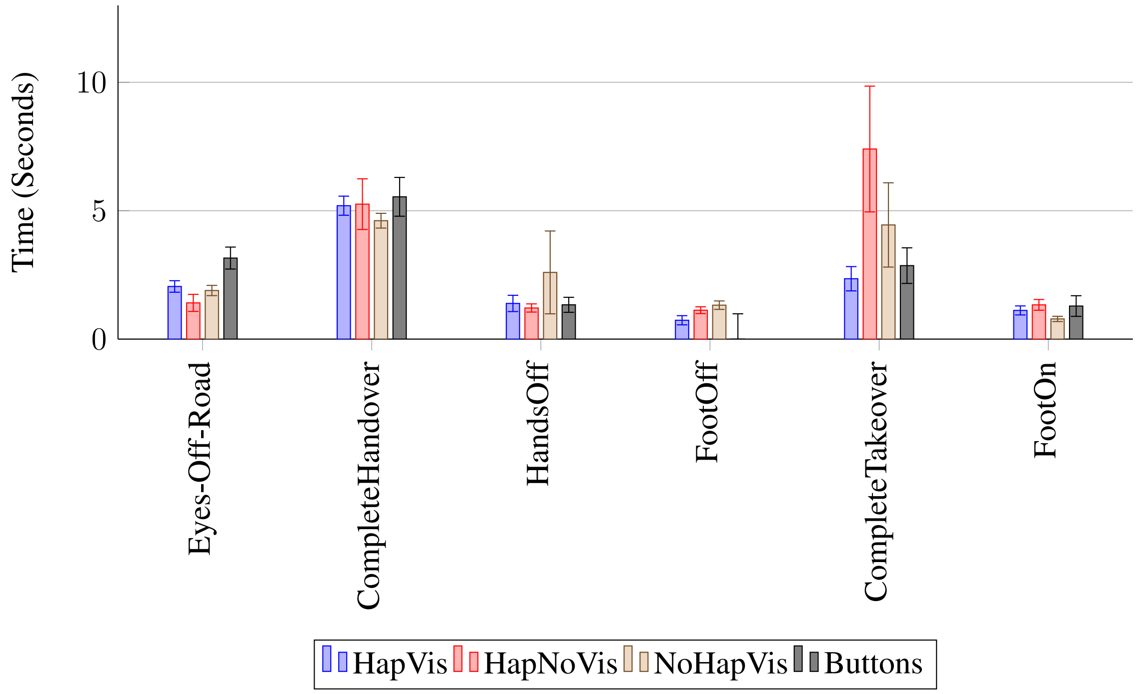


Figure 5.23: Experiment 7: Time Observations (including Buttons).

3 long glances during handover occurred (1 HapNoVis, 2 NoHapVis), usually due to interruptions in the process (when, for example, the participants stopped pulling the paddles before the handover was complete).

Driving Behaviour

Driving had outliers in number of micromotions (2 HapNoVis), where the values were excluded for evaluation as they differed more than two standard deviations from the mean. The evaluation with repeated measures ANOVA of the lane deviation during handover between conditions showed significant differences for Haptic ($F(1,13) = 5.88$, $p = 0.03$), where Haptic-On had less deviation ($M = 21.58$, $SD = 0.74$) than Haptic-Off ($M = 21.99$, $SD = 0.62$). No differences with repeated measures ANOVA were found for Visual ($F(1,13) = 1.02$, $p = 0.33$). The number of micromotions evaluated with repeated measures ANOVA showed no significant differences (Haptic: $F(1,12) = 0.15$, $p = 0.70$; Visual: $F(1,11) = 0.09$, $p = 0.77$).

Driving within the conditions, evaluated with t-tests ($t(df)$) or Wilcoxon tests (V), for not normally distributed data, showed no significant results for the number of micromotions of HapVis ($V = 29$, $p = 0.12$), but lane deviation ($t(13) = 2.58$, $p = 0.02$), where the handover had less deviation ($M = 21.48$, $SD = 0.72$) than the baseline ($M = 21.94$, $SD = 0.87$). Neither NoHapVis (lane deviation: $t(13) = 1.77$, $p = 0.02$; number of micromotions: $V = 12$, $p = 0.23$) nor HapNoVis (lane deviation: $t(13) = 1.54$, $p = 0.15$; number of micromotions: $V =$

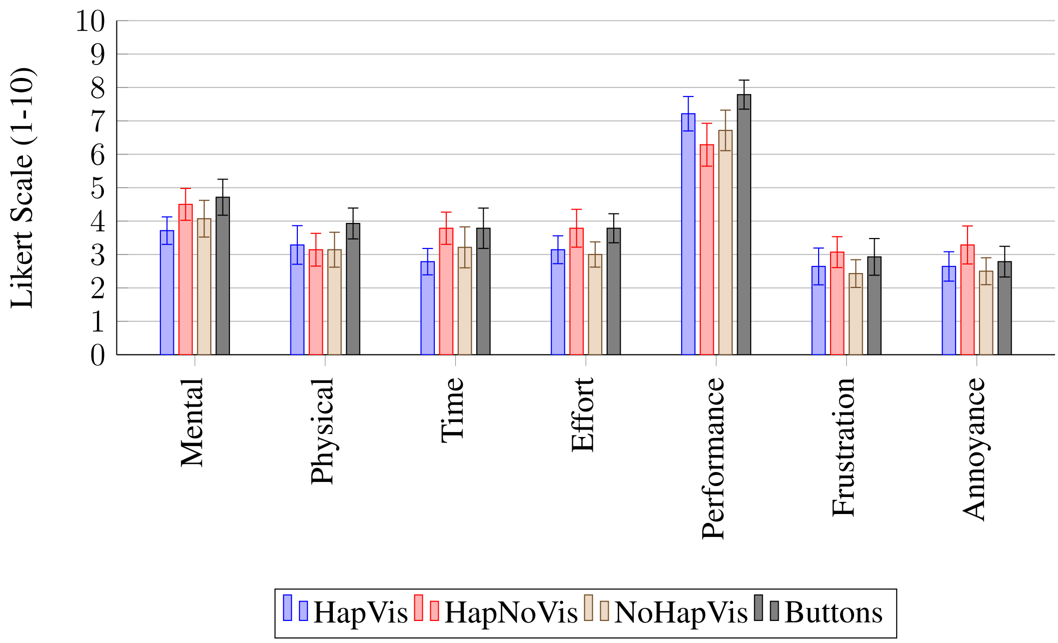


Figure 5.24: Experiment 7: Perceived workload; significant results are in bold font.

20.5, p = 0.30) showed significant differences for driving.

Subjective Data

The evaluation of overall perceived workload showed no statistical difference with repeated measures ANOVA for Haptic ($F(1,13)$ = 0.56, p = 0.47) or Visual ($F(1,13)$ = 1.96, p = 0.19). The ratings of the single categories can be seen in Figure 5.24. The evaluation of the additional ratings with repeated measures ANOVA showed no significant differences for complicated (Haptic: $F(1,13)$ = 0.09, p = 0.77; Visual: $F(1,13)$ = 0.00, p = 1.00), pleasant (Haptic: $F(1,13)$ = 0.41, p = 0.53; Visual: $F(1,13)$ = 1.59, p = 0.23) and comfortable (Haptic: $F(1,13)$ = 0.89, p = 0.36; Visual: $F(1,13)$ = 0.80, p = 0.39). For disruptiveness there was no difference found for Haptic ($F(1,13)$ = 2.07, p = 0.17), but for Visual ($F(1,13)$ = 8.97, p = 0.01), where Visual-Off was rated as more disruptive (*median* = 3.5) than Visual-On (*median* = 2). When asked if the condition influenced the trust in the system, 6 participants chose *no*, 5 *yes* and 3 *maybe*. The evaluation with repeated measures ANOVA of the trust ratings showed no significant differences (Haptic: $F(1,13)$ = 0.15, p = 0.71; Visual: $F(1,13)$ = 1.89, p = 0.19). Additional subjective and trust ratings can be seen in Figure 5.25.

The rating of how well participants felt the thermal feedback with and without the visual bar with Wilcoxon test showed no significant differences (V = 10, p = 0.57, both *median* = 2). The ranking of the conditions, see Figure 5.26, included Buttons, which was ranked least favourite (Rank 4) most often. HapNoVis was the least preferred condition using the gear paddles. NoHapVis was rated most often as most favourite, closely followed by HapVis.

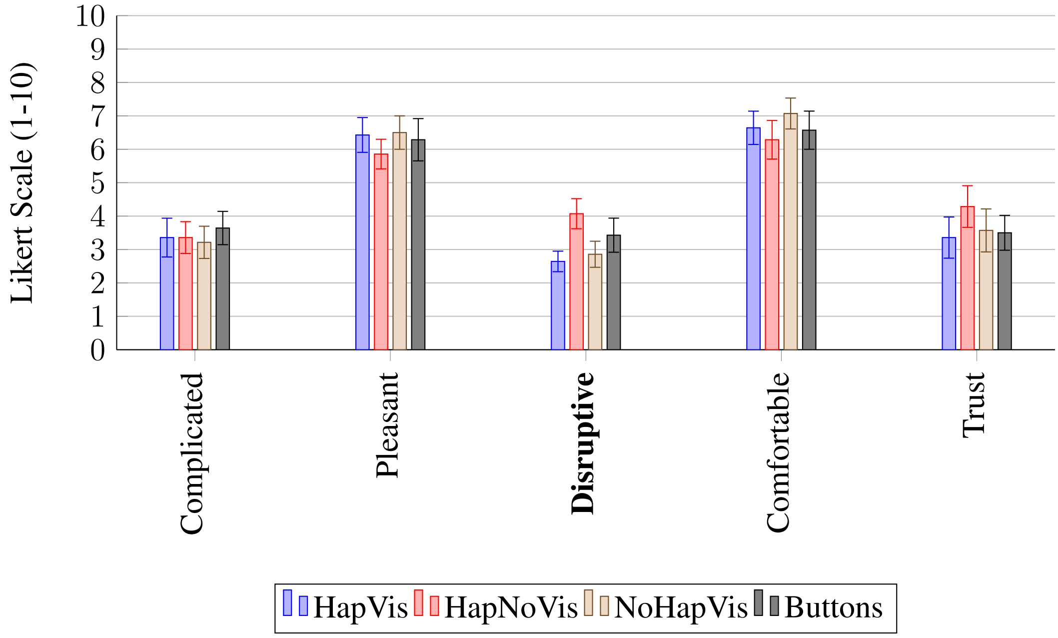


Figure 5.25: Experiment 7: Additional Subjective and Trust Ratings; significant results are in bold font.

HapVis was most often ranked into the top two positions.

The addition of haptic feedback was received diversely. *P01* disliked the vibration and commented that *the haptic feedback felt like the system was faulty, that [...] it was buzzing, and when the steering wheel moved, it just felt [like] the system was broken. The buttons and the voice over was much cleaner* and *P13* noted that *the haptic feedback [on] the steering wheel does not help me trust the system more and it's just annoying and irritating (unnecessary).* However, *P08* wrote that *phone and various controllers use vibrations as a form of feedback, so this is the form which felt most natural. P05* mentioned that *all options felt very similar and none were difficult or complicated. I didn't notice the thermal feedback.* Additionally, participants commented that *the system itself is generally what would need to build/hold my trust... Not necessarily the handover method. Once this is set and understood - then I would trust it* (*P09*) and *the longer the experiments went on the more comfortable I became with the systems. Towards the end I was aware that I was taking my eyes off the road and traffic conditions for long periods of time compared to the first test condition* (*P07*).

The lack of visual progress bar was noted as *fine as I was using the vibration rather then progress bar to know when the system was activated* (*P08*). *P09* commented: *On reflection, maybe nicer to have the progress bar, but not essential at all. The other confirmations (vibrations and audio) felt like enough. But on the other hand, progress bar is more akin to regular steering wheel functions that I'm used to. P06* noted that *the visual cue made me feel more confident at the system in that I can see the progressing of the operation via my input. P12 felt that without the visual timer bar it took longer, although just a mind trick, the timer*

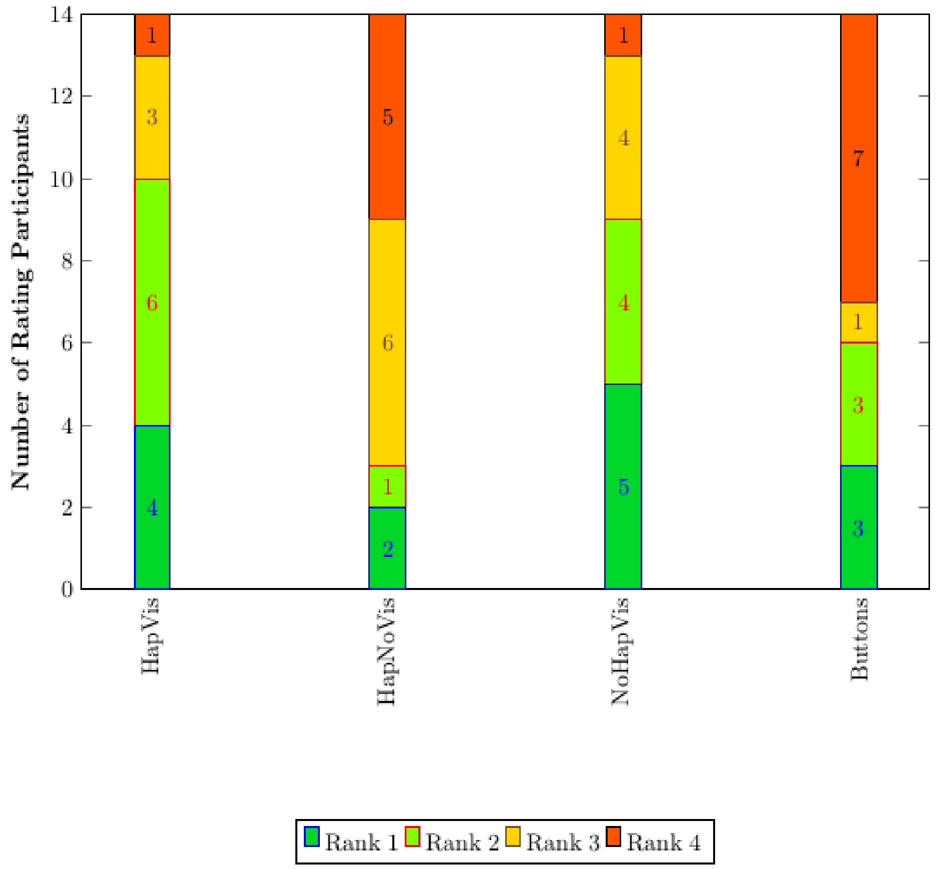


Figure 5.26: Experiment 7: Ranking of Conditions.

bar I feel, helps, and *P13 was looking for feedback on cluster and it wasn't there - I trust more the visual feedback with the progress bar than waiting for other form of feedback*. *P08* wrote that *thermal had little impact as this was insignificant over such a short period, but vibration was good as this allowed me to focus on the road rather then watching [the] progress bar* and *P03* found *having the vibration was more involving*. *P12* noted that they had *slightly more confidence in this due to the vibration feedback, [but] didn't really notice the temperature change*. Other participants shared this view on thermal feedback: *Heat sensor... Not really needed?* (*P09*); *The warm to cool and back controls seem pointless?* (*P10*); *didn't really feel hot/cold that much, doubt its a very good indicate of an affirmative action* (*P01*) and *couldn't personally feel the change in temperature on the handles* (*P11*).

Comments on Buttons described the condition ambiguously. On the one hand Buttons were *more fiddly* (*P07*) and *not great - too many buttons in close proximity, I had to think which one to choose and there was a high chance I'd get it wrong* (*P13*). *P10* noted that *while I felt buttons would be easier to use than the paddles in fact I found the buttons harder to locate the correct spot*. But on the other hand, they were *most natural* (*P05*) and *slightly more effort than simply tapping a paddle, but... I kind of preferred it! Paddle seems to me something I* *could tap by accident, this felt more definitive as an action and almost impossible to do by accident. Would have preferred vibration confirmation though* (*P09*). Still, most participants *prefer using the paddles* (*P04*),

Comparison of Buttons and Gear Paddles

The comparison of time observations between using buttons and gear paddles to initiate the control transfer with t-tests (*t(df)*) or Wilcoxon tests (V), for not normally distributed data, showed a significant difference for eyes-off-the-road time, see Table 5.19. A more detailed look showed that the time to look down was significantly different between Buttons and NoHapVis, where the time to look down was longer in Buttons (M = 1.03, SD = 0.59) than NoHapVis (M = 0.13, SD = 0.24), resulting in longer overall eyes-off-the-road-time (Buttons: M = 3.16, SD = 1.60; NoHapVis: M = 2.16, SD = 1.24).

Eyes-Off-Road	Down	Complete Handover	Hands Off	Foot Off	Complete Takeover	Foot On
V = 87 $\boldsymbol{p}$ **= 0.03***	V = 78 $\boldsymbol{p}$ **= 0.003***	V = 71 p = 0.26	V = 52 p = 1.00	V = 43 p = 0.58	V = 22.5 p = 0.65	V = 53 p = 1.00

Table 5.19: Experiment 7: Statistics for the Comparison of Time Observations between Buttons and Gear Paddles; significant results are bold and marked with an asterisk.

The comparison of the driving evaluated with t-tests (*t(df)*) or Wilcoxon tests (V), for not normally distributed data, showed no significant differences for lane deviation ($t(13)$ = 0.12, p = 0.90) and number of micromotions (V = 33, p = 0.23) and there were no significant differences found for subjective data between Buttons and NoHapVis, see Table 5.20.

Overall Workload	Complicated	Pleasant	Disruptive	Comfortable	Trust
V = 71.5 p = 0.07	V = 24 p = 0.44	V = 33 p = 1.00	V = 45.5 p = 0.27	V = 29 p = 0.44	V = 27 p = 1.00

Table 5.20: Experiment 7: Statistics for the Comparison of Subjective Data between Buttons and Gear Paddles; significant results are bold and marked with an asterisk.

5.4.7 Experiment 7 Discussion

This experiment applied thermal and vibrotactile feedback to inform on the process of control transfer for autonomous features in a vehicle. It was expected that the localised haptic feedback would help drivers to let go of the steering wheel and accelerator pedal faster after completed handover. But these reactions were not influenced by the presence of haptic feedback, so *Hypothesis 1* could not be corroborated. Furthermore, it took participants longer to return their foot to the accelerator pedal after takeover in the haptic condition. Haptic feedback did not improve reaction times. However, changes in the visual feedback had an effect on the timings: drivers took longer to take their foot off the accelerator pedal without the visual progress bar present. The thermal feedback did not seem to be enough to replace the information presented by the progress bar. Some participants mentioned in the open text comments that they could not feel the thermal feedback or considered it unnecessary and when rating how well participants could feel the temperature changes, the rating was on the lower end of the scale. Even though the temperature change was at the fastest rate and highest extent we observed so far, it seems to still have been too subtle within the short time frame of 2s for some participants.

Hypothesis 2 claimed that haptic feedback would increase trust in the system and positively influence driving behaviour. Participants commented that the trust in the system was not influenced by the condition, but rather their familiarity with the system itself. When asked directly, some remarked that the control transfer feedback might have influenced their trust, but the evaluation of the trust rating between conditions did not corroborate this. The driving behaviour was influenced by the presence of haptic feedback: less lane deviation was found with haptic feedback than without. With both haptic and visual feedback present, the lane deviation was improved during handover compared to baseline driving. The number of micromotions was not found to be different, even when lane deviation was improved. This would suggest that participants steered more steadily with both haptic and visual feedback present, increasing driving behaviour. *Hypothesis 2* could, therefore, be partly corroborated.

Participants reacted ambiguously towards haptic feedback. Some participants preferred it, other deemed it too much or unnecessary, especially the thermal feedback. Vibration was more often considered a reassuring addition, thermal feedback was almost exclusively remarked on negatively. The ranking at the end of the experiment almost tied the two conditions HapVis and NoHapVis for the first two spots, suggesting that the visual feedback was the more important factor, not haptic. *Hypothesis 3* could, therefore, not be corroborated. This aspect might, however, be influenced by the participant pool: as JLR employees, the participants were potentially biased towards new technologies, as they would not experience them naively as a novel interaction, but connected to consequences or experiences attached to their specific roles within the corporation. This limitation might hold true for several observations of the experiment, but especially for preference ratings. The different conditions should be tested with more naive users in the future, to gain more versatile and diverse feedback.

Hypothesis 4, expecting that the lack of visual feedback would lead to less eyes-off-the-road time, was not corroborated. Neither haptic nor visual feedback influenced the overall eyes-off-the-road time. Long glances away from the road occurred both with and without visual feedback and were brought on by difficulties during the control transfer. Comments and rankings indicate that participants felt more confident with visual feedback present, even when they did feel comfortable with relying on vibration. Furthermore, the lack of visual feedback was rated as significantly more disruptive, highlighting again that thermal feedback alone seemingly did not convey enough information to prepare participants for the upcoming vibration.

The comparison between buttons and gear paddles as transfer mechanisms showed differences in overall eyes-off-the-road time by 1s, caused by a significantly longer amount of time spent looking down on the steering wheel when using buttons. There were, however, no long glances away from the road in condition Buttons, while there were two in condition NoHapVis. This corroborates *Hypothesis 5* only partly.

5.5 Chapter 5 Discussion

Three experiments explored thermal feedback in combination with vibrotactile feedback on the steering wheel for notifications. The first two experiments additionally looked into unimodal thermal cues, exploring their use for notifications of different levels of urgencies and for two types of information. Thermal stimuli were consistently rated as less urgent than vibrotactile or bimodal haptic stimuli, suggesting their use for non-urgent notifications. But they also were missed more often. The stimuli design of Experiment 5 was aligned to vibrotactile feedback used in previous research, in which they combined vibration with audio and visual feedback for urgent notifications. The cues, therefore, were short and, especially for low and medium urgency notifications, very subtle, leading to many missed stimuli. While participants rated in the questionnaire at the end that bimodal cues felt more urgent, this sentiment was not mirrored in the rating of the perceived urgency of the cues at the beginning of the experiment. Furthermore, the recognition of bimodal stimuli took longer than vibrotactile stimuli alone, which makes the cues unsuitable for urgent notifications during driving, as fast reaction would generally be needed to avoid danger. In addition, the bimodal representation did not increase recognition rate compared to vibrotactile. The expected benefits of the bimodal condition, therefore, could not be observed. Participants reported a feeling of uncertainty connected to thermal feedback: they had sometimes problems distinguishing especially subtle warm temperature changes from the natural warming of their hands on the steering wheel. Additionally, they reported problems with the differentiation of the length of temperature presentation, which encoded the different levels or urgency. Three levels, in combination with the subtle changes of medium and low urgency cues, led to a high number of missed and falsely identified thermal stimuli.

The second experiment used longer thermal cues, chosen from the most successful combinations from Experiment 2. Three sets of stimuli were chosen, all of which showed high recognition rates and low number of false positives, for both directions of temperature changes. Two different types of information were presented: the Nature of a message, represented by the direction of temperature change (warm/personal, cold/work) in both thermal and bimodal tactile cues, and the Importance of a message, represented by either the combination of length of temperature presentation and the style of return to neutral in the thermal, or vibration pattern in the bimodal haptic condition. The study led to high recognition rates for all stimuli, apart from the thermal low importance personal cue, the short warm temperature change. Again, participants reported that they had problems distinguishing the warm, especially the short warm, cues from the natural warming of the hand. The other three thermal cues were easier recognised, with rates between 88% and 92% even slightly higher than the bimodal cues with 86% to 87%. Even though participants ranked the bimodal stimuli as easiest to identify, the thermal cold high importance cue had the highest recognition rate (92%). This could be due to the fact that some participants mixed up the two vibration patterns. The direction of temperature change, the Nature of the message, seemed to be easy to recognise by participants, mirrored in their rating at the end of the experiment. The mapping of warm to personal and cold to work seemed to benefit from natural associations with temperature that could not be as easily replicated with vibration. Furthermore, the uncertainty of thermal feedback was overcome by starting the cue with vibration in the bimodal condition, alerting participants to an upcoming thermal cue. This combination was reported to work well and showed very high recognition rates, especially for direction of temperature change. With increased vibration patterns, maybe even designed by participants themselves, this could be extremely effective. As thermal preferences differ between individuals, adaptive thermal feedback could increase recognition of thermal cues as well.

In the last experiment, thermal and vibrotactile cues were added to a multimodal design for the transfer of control of an autonomous feature. The thermal feedback represented the progress of the control transfer, while vibrotactile feedback announced the completion of the transfer. The transfer of control was achieved by simultaneously pulling both gear paddles, on which the thermal and vibrotactile feedback was presented, with additional vibration on the accelerator pedal. The successful transfer was completed after 2s, leaving a rather short time period for the thermal cue. While vibration was welcomed by most participants, the thermal cue was not considered necessary or helpful. In one condition, the visual progress bar was completely replaced by the temperature change, which led to an increased feeling of disruptiveness. However, the addition of bimodal tactile feedback to the multimodal cue improved the driving behaviour during the handover of control to the car.

5.6 Conclusions and Research Question 3

In this chapter, three experiments were presented to answer Research Question 3:

How effectively can thermal feedback convey notifications in a car in a
a. unimodal setting?
b. bimodal tactile setting?

The effectiveness of thermal unimodal notifications depends highly on the stimuli design and the intended use case. Short, especially warm, temperature changes are often missed or mistaken for the natural warming of the hands of the steering wheel. Even cues that have been successful in previous experiments, where they were presented on the fingertips of one hand, have reached low recognition rates when presented on the thenar of both hands while grasping the steering wheel. The driving task in those two experiments differed as well, which could have had an influence on the workload and in turn could have influenced the recognition of the cues. This highlights that not all factors impacting the recognition of thermal cues have been explored and fully understood yet. While the presentation of three levels of information led to many recognition errors, especially for thermal only cues, two levels were well recognised. Overall, thermal feedback has been consistently rated as less urgent than vibration and bimodal tactile cues. In combination with the longer recognition time compared to other modalities, this recommends thermal as feedback for non-urgent information. High and long temperature changes led to high recognition rates, in some cases even higher than bimodal tactile feedback.

The addition of vibrotactile feedback to thermal cues can be highly beneficial to the recognition of thermal changes: participants commented that they were alerted by the vibration and then focused on the temperature. The uncertainty reported with thermal feedback could be overcome by prompting the cue with vibration. Not only does this eliminate the uncertainty, it also minimises the effect of false positives, as the initial temperature change is highlighted by the vibration and the return to neutral can be more easily distinguished. This led to high recognition rates and preference ratings. In addition, thermal feedback can have associations that can increase the recognition, as shown by the mapping of warm to personal and cold to work, which seemed to be more memorable than vibration patterns. Both factors, however, might benefit from adjustable and personalisable cues, to accommodate preferences and personal associations. Haptic feedback can improve driving behaviour, as shown in the last experiment. However, more detailed studies would have to determine if thermal feedback influenced this effect or if it was mostly due to the vibrotactile cue. The next chapter will summarise the findings and conclude this thesis.

Chapter 6

Conclusions

This thesis investigated the feasibility of thermal feedback use during the demanding task of driving. The thesis statement in *Introduction* read as follows:

> Haptic feedback within cars is used to reduce visual distraction during driving, one of the main contributors to crashes. This research explores aspects and applications of thermal feedback for in-car use to convey information to the driver non-visually. Results show that thermal cues can be used to convey information to the driver accurately and non-urgently and its effectiveness can be enhanced through multimodal combination with vibrotactile feedback and offers a rich, new modality to broaden the design space of tactile in-car feedback.

This statement was supported by research discussed in the following chapters. The exploration of thermal feedback during driving started in Chapter 3 with a single device to convey direction, presenting binary information in the form of direction of temperature change (warm/cold) to see how well this minimal information could be perceived and what influence it would have on the driving performance. Chapter 4 introduced the information provided by spatial placement of multiple devices on the steering wheel and explored its influence on directional information. Chapter 5 described three studies on thermal and vibrotactile bimodal cues and their effectiveness for different kinds of notifications. These user experiments were conducted to answer three Research Questions and their results will be summarised and discussed in this chapter. In addition, contributions and limitations of the thesis will be discussed and future work outlined.

6.1 Research Question 1

How accurately can thermal feedback give binary direction cues in an automotive setting (with one thermal device)?

To answer this question, two simulator studies were conducted, as discussed in Chapter 3. One thermal device was presented to participants on the desk in front of them, while they drove one-handed. Experiment 1 investigated fixed warm and cold cues, where warm prompted a lane change towards the right and cold towards the left. Thermal feedback was compared to speech and showed higher workload for factors mental and physical demand, performance and frustration. Thermal cues were recognised with high accuracy during driving, with of up to 97% correct recognition. However, the return of the temperature to neutral after the cues was often misinterpreted as a new cue, a false positive.

Experiment 2 investigated several stimuli designs, testing the influence of several factors on improving recognition and reducing the number of false positives. No solution was found that ensured high recognition rate and low rate of false positives. The design process for binary thermal feedback has to prioritise one aspect. In addition, recognition time for warm stimuli was influenced by how much the temperature was changed and how long it was presented. Recognition time of cold stimuli was not influenced by any design factor.

High recognition rates would suggest that the modality can be effectively used with direction of temperature change providing binary information. However, false positives can have a reducing influence on the accuracy of the feedback. This might not pose a problem for feedback of informational character, but can effectively negate directional cues. In answer to Research Question 1: binary thermal feedback is not suitable to provide accurate directional cues in a driving context.

6.2 Research Question 2

How accurately can thermal feedback give direction cues in an automotive setting with the spatial information from multiple thermal devices?

Experiments 3 and 4 in Chapter 4 used multiple devices on the steering wheel for turn-by-tun navigation to answer this question. The navigation in both experiments included ahead warnings 200m before the turn and another cue right at the turn. The first thermal navigation design, used in Experiment 3, was compared to audio feedback. It indicated the direction of upcoming turns by warming the corresponding side of the steering wheel, while cooling the opposite side. The association of warm towards destination was used in previous research and confirmed by participants in the first two studies. Thermal feedback had high recognition rates of over 90%, but was rated higher on workload and lower in additional subjective ratings. Participants commented on the simultaneous presentation of warm and cold stimuli as confusing.

Therefore, Experiment 4 only presented warm stimuli on the turning side of the steering wheel and compared the navigation to cutaneous push feedback, an equally novel cue which also engages the tactile sense. Recognition for thermal feedback was more divergent, as recognition for ahead warnings reached 98%, while only 87% of turns were correct. In addition, workload for thermal feedback was higher in every rated aspect and participants preferred cutaneous push feedback. In both experiments, participants commented on an overall sense of uncertainty around thermal feedback, not being sure if the warming was natural warming of the hand grasping the wheel or a stimulus. This led to an increased need to pay attention to the cues.

The spatial information presented through the location of multiple thermal devices could be used effectively to give navigation information in both studies. Therefore, to answer to Research Question 2: spatial thermal directional cues, provided by multiple thermal devices, can be accurately used during driving. Further studies should, however, investigate the influence of long term use on familiarisation and different workload conditions to ensure that accuracy levels can be sustained.

6.3 Research Question 3

How effectively can thermal feedback convey notifications in a car in a
a. unimodal setting?
b. bimodal tactile setting?

This questions was explored with three simulator studies with thermal and vibrotactile feedback for different kinds of notifications, discussed in Chapter 5. Experiment 5 investigated the effectiveness of thermal feedback to increase the feeling of urgency. The thermal cues were designed to fit vibration patterns of three differing urgency levels and were presented at the same time, resulting in some subtle cues. Perceived urgency was rated for uni- and bimodal cues and showed that thermal cues were consistently rated as less urgent than both vibrotactile and bimodal tactile cues, but also missed more often. The addition of thermal feedback did not increase the feeling of urgency compared to vibration in this subjective rating, even though participants commented in the questionnaire that bimodal cues felt more urgent. Recognition was in general better for cues including vibration. Bimodal feedback led to slower reaction times than vibration alone, which makes bimodal feedback unsuitable for urgent notifications that require fast reactions to avoid dangerous situations.

Experiment 6, therefore, explored the use of bimodal tactile and unimodal thermal feedback to convey non-urgent notifications: message information with two levels of information. Direction of temperature change encoded the Nature of a message (warm-personal / cold-work), vibration patterns in the bimodal, or length of cue in the thermal condition, encoded Importance. The ThermalLowPersonal cue (short warm cue) had the single worst recognition (60%) and ThermalHighWork the best (92%), while all other cues had recognition rates between 86% and 89%. The factor Nature achieved especially high recognition in the bimodal tactile modality.

Experiment 7 added bimodal tactile feedback to a set of multimodal cues for transfer of control. The feedback was introduced to inform drivers on the progress of the control transfer, to affirm when drivers could disengage the steering wheel and pedals. Thermal feedback was used to inform on the progress of the transfer, vibration on its completion. The addition of bimodal feedback positively influenced driving behaviour, but thermal cues could not successfully replace a visual progress bar.

These results show that thermal feedback can be used to convey notifications unimodally and bimodally with vibration, dependent on cue design. Bimodal feedback was generally preferred and had best results when presenting vibration before the temperature change for two levels of information. To answer Research Question 3: thermal feedback can effectively convey notifications in the driving context, both in a uni- and bimodal setting with vibration.

6.4 Contributions and Recommendations

This thesis contributes novel insights into the use of thermal feedback during driving. The main contributions are: (1) first examination of design factors for binary thermal feedback during driving; (2) exploration and effective use of spatial thermal feedback for in-car navigation purposes; (3) investigation of perceived urgency for uni- and bimodal tactile notifications on the steering wheel; (4) evaluation of perceptability of uni- and bimodal tactile cues during driving.

Design recommendations have been extracted from the findings of the thesis and are summarised in Table 6.1. These recommendations are based on observations with specific design factors and ranges used in this thesis and need to be interpreted with this in mind.

Design Recommendation	Chapter
(1) Thermal cues took 1.82s longer to be recognised than audio cues. Thermal feedback should be used for non-time-critical cues. **(2)** Binary cues of high extent (6°C) and length (3s and 6s) of warm temperature changes led to high recognition, but also to a high number of false positive recognition at the return to neutral and long recognition times. Cue design has to prioritise between high recognition and low number of false positives.	3
(3) Direction information with thermal spatial information achieved high recognition rates of 87% to 97%. Thermal spatial information is suitable for navigation. **(4)** Participants reported confusion with warm and cold temperatures presented an opposing hands at the same time. Thermal feedback should not be presented on both hands with opposing direction of temperature change for navigation.	4
(5) Thermal cues, in the range tested, were rated as less urgent than vibrotactile cues. They should be used for non-urgent feedback. **(6)** Warm temperature changes of short duration were often missed when presented during vibration. Short thermal cues, especially warm temperature changes, should not be presented during vibration. **(7)** Bimodal thermal and vibrotactile cues take longer to recognise than vibration alone. Urgent vibrotactile warnings should not be combined with thermal feedback. **(8)** Vibration patterns followed by temperature can be used effectively and reduced the feeling of uncertainty sometimes experienced with thermal unimodal cues. Bimodal tactile cues should present the vibration before the temperature changes. **(9)** Short warm temperature changes on the steering wheel had poor recognition. They should not be presented on the steering wheel during driving. **(10)** Long cold thermal changes (6°C presented for 3s with angled return to neutral) were recognised with the highest accuracy (even when compared to bimodal cues). These cues should be used for important thermal only feedback. **(11)** Short temperature change during transfer of control could not compensate the lack of a visual progress bar. Short temperature changes should not be used to replace visual information of processes.	5

Table 6.1: Design recommendations overview collected from the experimental findings of this thesis.

6.5 Limitations and Future Work

This section will discuss limitations of the thesis and propose ideas for future work.

6.5.1 Simulator Studies

Thermal feedback was only investigated in simulator studies, a necessity to ensure that the presentation of this feedback, novel within the car, would not lead to hazardous situations and endanger participants and experimenters. However, the effects of real world driving on the perception and usability of thermal feedback is unknown. No significant differences in lane deviation have been found for any studies but the last, which was the only one including visual feedback, therefore, no definite conclusion can be drawn on the influence of thermal cues on driving behaviour. However, thermal feedback increased workload, which has been shown to have negative effects on driving [162, 169]. More studies are needed to evaluate the impact on thermal feedback on driving, before the feedback can be safely tested in real world driving.
Most studies presented in this thesis were conducted in a low fidelity simulator, which could have impacted immersion into the driving task. High fidelity simulators could provide a more realistic driving experience, which could ultimately have an influence on the perception of the thermal modality.

6.5.2 Simple Driving Tasks

Most driving tasks in this thesis were limited to lane change scenarios and turn-by-turn navigation within empty streets. More complex tasks should be evaluated in future experiments. The last experiment used an environment with heavy traffic, but thermal changes were presented only for a few seconds. Perception studies with light and heavy traffic on different kinds of roads and potentially with pedestrians should be conducted in the future. All these factors would potentially increase the workload of participants during normal driving and the impact of additional workload added by thermal feedback could be evaluated in detail.

6.5.3 Selection of Use Cases

Use cases for the experiments were chosen from a vast number of possible scenarios within the car. Directional cues can be used in many different scenarios and are not limited on prompting lane changes or navigation. The notifications tested in this thesis were designed for very specific use, with many more possibilities awaiting. Thermal feedback could be used for presentation of the car state, indicating low fuel or tyre pressure. Or it could indicate low outside temperature, warning the driver of possible ice on the road. Participants suggested many different use cases, which could all benefit from thermal presentation and warrant investigation in future studies.

6.5.4 Pre-Set Thermal Cues

The thermal feedback used within this thesis was chosen in accordance with previous work or to allow for cues within a set time frame. Choosing a neutral base temperature led to consistent changes for all participants. But thermal perception can vary between individuals, as can thermal comfort. Temperature changes which some declare barely noticeable are described as very hot by others. For practical and commercial use, this variability will have to be taken into account and adaptable, personalisable cues need to be possible. Future research needs to investigate what cue factors should be adaptable and how to still ensure common associations and interpretations of these differing stimuli.

6.5.5 Different Thermal Devices

Peltier devices of two different sizes were used for the experiments. While the type of device and the capabilities were the same, the area of thermal stimulus presentation has an impact on the perception due to spatial summation [69, 67]. Experiment 3 and 4 use different sized Peltiers, but twice the number of devices for the smaller ones. It is not clear if this balances perception or not. Experiment 5 only used one small device and had some very short cues, while Experiment 6 used the large devices with longer cues. The impact of the size of the different Peltier devices should be tested in detail. Furthermore, a more fitting prototype, such as a thermal steering wheel, instead of Peltier devices manually taped to the wheel, could influence perception and especially comfort enormously.

6.5.6 Influence of Hand Placement

The first two experiments evaluated thermal stimuli on a device placed in front of the participants, later experiments had devices attached to the steering wheel. Results of Experiment 6 showed that cues that tested well under the first condition had significantly lower recognition rate when presented on the steering wheel. Participants commented that they had trouble distinguishing between thermal cues and the natural warming of their hand caused by grasping the steering wheel. Future research should look into this effect and determine how sensing the actual temperature of the hand and adapting cues according to this as the new base temperature influences perception and comfort.

6.5.7 Limited Location

Thermal feedback was only presented on the hands, either in front of the driver or on the steering wheel. If autonomous cars become more prevalent, hands might be rarely placed on the steering wheel or other parts of the car. However, drivers will still be seated and using seat belts. These locations could be used for thermal feedback, the same way they are used for vibrotactile feedback. Perception and comfort studies would have to confirm the feasibility of such feedback. The influence of clothing and temperature build up on the seat through long-time sitting would also have to be investigated in more detail.

6.5.8 Short Duration Studies

Experiments usually took around an hour and thermal feedback was presented for a fraction of the time. It is unknown if and how thermal perception for differing cues on a small area of the skin would change over a longer period of time. Perception could increase due to better familiarity with the cue. However, longer exposure could lead to unexpected reactions of the skin's thermal sensing. Skin adapts to temperatures over time, but how does it react to many differing cues presented on the same location? Future work should evaluate the effect of long exposure to differing thermal cues.

6.5.9 Participant Demographic and Number

Participants were small in number and biased towards higher education and similar in age and gender, as the focus of the experiments was to establish a basic understanding of the effect of thermal feedback in the car rather than ensuring diverse participant groups. Recruitment was primarily within institution (university or company), no specific focus was put into recruiting more diverse groups from different backgrounds and diverse demographics. Investigating perception over a more diverse group and in higher number could yield important insights. Age has been shown to influence thermal perception and cultural background (such as land of origin and its climate) could have an influence on perception and workload.

6.6 Conclusions

Driver visual distraction can be mitigated with tactile feedback. This thesis offers the first insights into the effectiveness of novel thermal feedback for in-car applications. Several factors of thermal perception were investigated during the highly demanding task of driving and thermal feedback was applied to some of the use cases most common in the vehicle.

Findings showed that some thermal cue designs can be identified with high accuracy, both uni- and bimodally, and should be used for non-urgent feedback due to longer recognition times. Direction of temperature change proved to be the best recognised factor of thermal cues on the steering wheel, further enhanced when presented after vibration. These findings provide the basis for a richer and more diverse design space for tactile in-car feedback and can help to improve driver safety.

Appendix A

Appendix

A.1 Hardware Manuals

A.1.1 Thermal Bluetooth Board Manual

UGLA Bluetooth 2 Channel Heat Pump Driver
User Manual Rev 0.00

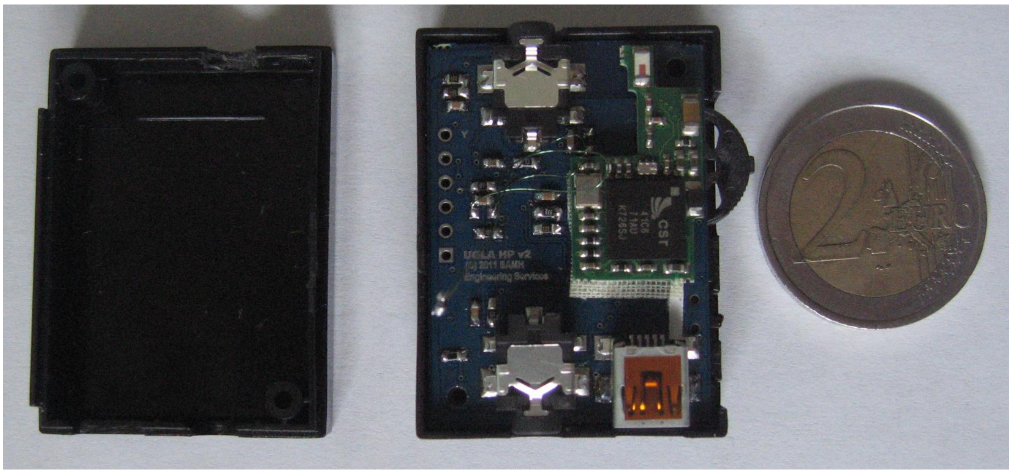


Figure 1 - Device with enclosure cover removed

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Operational Overview:

This device allows up to 2 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 4W per channel – the recommended minimum load resistance of the Peltier devices is 3.5ohms 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 a dedicated circuit separate from the PID control loop that monitors the temperature sensor of both channels. If

1) the temperature rises above about 48degreesC on any channel OR
2) any of the temperature sensors are disconnected OR
3) there is a short circuit across any of the temperature sensors

this circuit will shut down all power to the Peltier heat pumps and flag an exception (the LED will flash red).

Additionally, 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 (by looking for expected changes in temperature).

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 60 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 the Panasonic ERT-J1VG103FA thermistor. No other thermistors are 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) result in overshoot of about 1 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.

There is also an internal temperature sensor that measures the ambient temperature inside the enclosure. It is located just inside the roof of the top enclosure half.

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Device Connections and Setup:

This device is designed to connect to a host PC using Bluetooth serial port profile (SPP). It obtains power from a 4*AA NiMh battery pack that is specially wired to a mini USB jack which should be connected to the mini USB socket on the device. If the device is connected to a USB socket of a PC using a standard USB cable then there will not be enough current available to drive the heat pumps.

Important: In the battery pack it is essential only to use either NiCd or NiMh cells. Alkaline or Lithium AA cells may have too high an internal resistance and may not be capable of providing enough power to drive the heat pumps.

The Peltier heat pumps and their temperature sensing thermistors are supplied on separate heat sinks. They are connected to the device with a pair of 4-pole 2.5mm jack terminated cables. They should be connected to the 2.5mm sockets at the ends of the device.

Important: To avoid over heating and a burning hazard always ensure that the opposite side of the heat pumps is connected to a heatsink. Ideally that heatsink should have a rating of at least 10 degC / Watt.

Note: Both heat pumps (or at least their temperature sensors) must be connected to the device or else it will shut down to a fault state.

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Programming / Communication Reference:

The board has an onboard microcontroller that performs commands on demand from a host PC. The host talks to the board using a serial COM port over a Bluetooth SPP serial port profile wireless connection.
The COM port settings are BAUD = 460800, 1 start bit, 8 data bits, 1 stop bit, no parity and hardware flow control.

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.
(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 board 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 board 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 board 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.

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 Hex.

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

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```
UGLA Bluetooth 2 Channel Heat Pump Driver v0.00
Copyright 2011 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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The command CMD_SET_CHx_TEMP

This command is used to set the temperature of channel x where x is either 1 or 2 depending on which channel you want to set the temperature for.
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 2 to 0 degreesC send this command –

```
$CMD,0000,02
```

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 1 and 2 send –

```
$CMD,FFFF,01
$CMD,FFFF,02
```

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The command CMD_READ_CURRENT_TEMP

This command is used to read the temperature of channel x where x is either 1 or 2 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 2 send this command –

```
$CMD,0002,05
```

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

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

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The command CMD_READ_SETPOINT_TEMP

This command is used to read the temperature set-point of either channel.

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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The command CMD_SET_LEDs

Use this command to set the state of the RGB LED on the board. Once the LED state is set, it remains so until it is changed again regardless of any other commands that are performed.

The command type has the value 0x00, and the command argument is-

Revert to firmware control = 0x0000
RED = 0x0001 (i.e. bit 1)
GREEN = 0x0002 (i.e. bit 2)
BLUE = 0x0004 (i.e. bit 3)

So the LED colours can be combined by adding (ORing) the values together.

If successful, an ACK packet will be returned with 0 as its first argument and the CMD_SET_LEDs enumeration code as the second argument.

Example: To set the LED to ORANGE send this command –

```
$CMD,0003,00
```

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The command CMD_SET_ROC_LIMIT

Use this command to limit 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 2 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 enable this feature send the following command –

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

To disable it send this command –

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

This feature is enabled by default.

The following is typical of the output data, and it is output a couple of times per second(the third temperature is the ambient temperature) -

```
$SET POINT  ,+20,+20
$TEMPERATURE,+21,+19,+23
```

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Fault Events:

There are five circumstances that can cause a fault event -

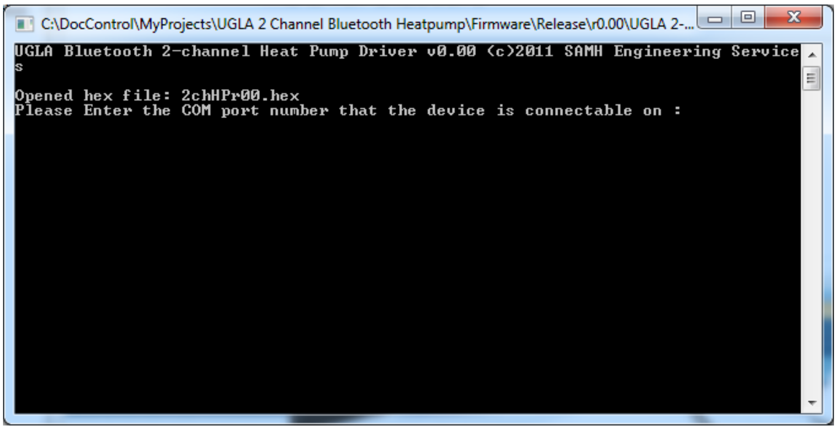
1) If any one of the active channels has an over temperature condition
2) If the temperature sense thermistor for any active channel is electrically disconnected
3) If the temperature sense thermistor for any active channel is electrically short circuited
4) If the thermistor for any active channel becomes detached from the heat pump and if that heat pump is driven in the hot direction for more than about 12 seconds
5) 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 (as per the list above).
The board will also shut down to a low power state and indicate a flashing pattern on the red 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 the power to the board must be cycled by removing then re-inserting the power cable.

Firmware Upgrade:



To perform a firmware upgrade, unzip the .exe and .hex firmware files to a folder on a windows PC. Make a note of the COM port number that the device is normally connected to the PC. Turn on the power switch while holding the navigation switch in. Run the .exe bootloader program. Follow the instructions displayed. Wait until the bootloader program has finished execution, then re-connect and use the board as normal.

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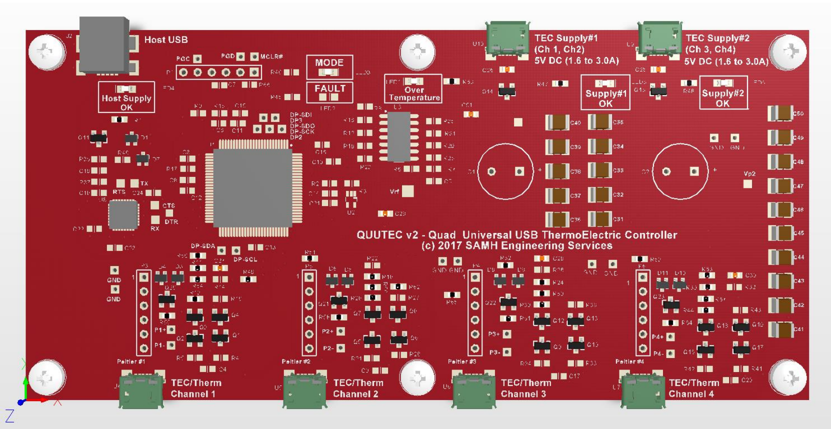
Document History

Revision #	Date	Changes
0.00	27/08/2011	Initial Draft

A.1.2 Thermal USB Board Manual

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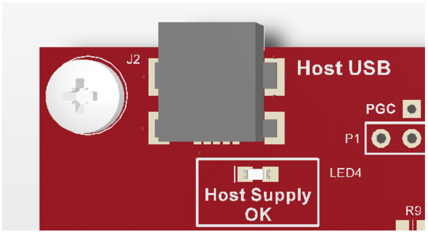
Thermistors with characteristics other than those listed above are not supported by this hardware.

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.

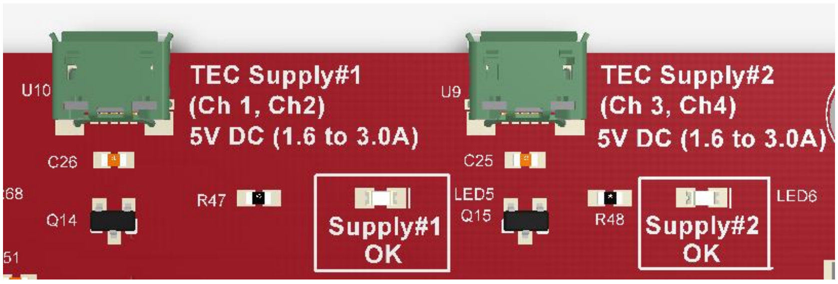
The steady state error between the set point and actual channel temperature is typically less than 1degC. Step changes of large magnitude (20 degrees) can result in overshoot of about 2 degC before settling to the set point temperature. The rate of change of temperature of the surface of the heat pump 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.

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:

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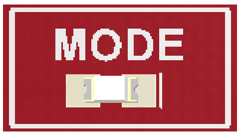
Programming / Communication Reference:

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.

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.2 Experiment 1

A.2.1 Experiment 1: Information Sheet

TempLane – Investigating Thermal Feedback for Lane Change Scenarios

INFORMATION SHEET

BACKGROUND

The goal of this user study is to improve safety in driving situations by providing navigational information through thermal feedback on the steering wheel.

TASK

The study is conducted in a driving simulator and will consist of four blocks. You will be asked to follow instructions given either through thermal feedback, both warm and cold, or audio instructions. You will perform the tasks sitting in a padded, adjustable chair. There will be a steering wheel securely attached to the desk in front of you. You will be holding the wheel throughout the experiment with one hand while driving. The other hand will be placed on the table next to the steering wheel and you will be asked to place your finger on the Peltier device (used for the thermal feedback). The simulator requires you to keep a virtual vehicle within the limits of the road and keep it inside a lane. You will get instructions to change lanes, either through audio commands ("right" or "left") or through thermal feedback (warm for right and cold for left). Please change to the next lane on the indicated side as fast and accurately as possible and try to stay inside the lane, whenever you are not actively changing into another. Please always only change one lane.

You will have time to get used to the simulator and the thermal feedback and the audio navigation in the first two blocks of the experiment, while keeping in the middle lane and reporting back the stimuli. In the third and fourth block you will be asked to follow instructions given by either audio or the thermal commands. In the beginning and after each block you will be asked to fill in questionnaires and will you have time to take a break.

INSTRUCTIONS

- Please place one hand on the steering wheel and the other on the table while driving.
- Please try to follow the instructions given by the system to the best of your ability and try to keep inside the lane. If not indicated otherwise, please follow the road straight ahead.

MISCELLANEOUS

- You will be wearing headphones throughout the experiment.
- The experiment is divided into blocks. You can rest between the blocks for as long as you need.
- You can withdraw from the study at any time without penalty. The data recorded until then will be destroyed.

IMPORTANT

The systems you interact with will not ask or store personal information and all data recorded are anonymised. 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. To take part in this study, the following criteria must be met:

- I am at least 18 years old
- I hold a full driving licence
- I have no visual impairments (not including wearing glasses or contact lenses)
- I have no neurological disorders (e.g. epilepsy)
- I do not suffer from motion sickness
- I do not have any sensory impairments

You will be given resting sessions between experimental conditions but please do not be afraid to ask for a break if required at any time during the study. Furthermore, if you feel unwell at any point, please let the experimenter know immediately so that medical attention can be given as soon as possible If you have any questions about the study or would like more information about our research in general, contact details are provided below.

CONTACT DETAILS

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Tel:	+44 (0)141-330-8430
Supervisor:	Professor Stephen Brewster
Email:	stephen.brewster@glasgow.ac.uk
Office:	Room S131, Sir Alwyn Williams Building (Computing Science), Glasgow, G12 8RZ, Scotland
Tel:	+44 (0)141-330-4966

This study has been approved by the Ethics Committee (Reference Number - D1483958803605).

This research is part funded by the EPSRC and Jaguar Land Rover.

A.2.2 Experiment 1: Consent Form

TempLane – Investigating Thermal Feedback for Lane Change Scenarios

CONSENT FORM

☐ I confirm that I have read and understood the Study Information Sheet provided to me for the above study and have had the opportunity to ask questions.

☐ The study has been explained to me, and I understand the explanation given and what my participation will involve.

☐ I understand that during the course of the study the experimenter will give additional instructions concerning the experiment and that the purpose of some of the instructions will only be explained at the end of the study.

☐ I understand that my participation is voluntary and that I am free to withdraw at any time, without giving a reason.

☐ I understand that the research data may be accessed by researchers working at the GIST, but that at all times my personal data will be kept confidential in accordance with data protection guidelines.

I have initialled the above boxes myself and I agree to take part in the study.

FULL NAME: ____

SIGNATURE: ____

DATE: ____

EMAIL: ____

Experimenter: Ms Patrizia Di Campli San Vito
(p.di-campli-san-vito.1@research.gla.ac.uk)

DATE, SIGNATURE: ____

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 -).

This research is part funded by the EPSRC and Jaguar Land Rover.

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Version No. 2 (March 2017)

A.2.3 Experiment 1: Questionnaires

Participant Number: ___________ TempLane_Beginning

Age: ___________

Gender: male ☐ female ☐ other ☐

Occupation / field of study: ____

Years of driving experience: ___________

Country, where driving licence was obtained: _____________________

Please rate your experience with the following:

	(none) 1 2 3 4 5 (much)
Experience with a driving simulator	|---¦---|---¦---|---¦---|---¦---|
Experience with audio navigation	|---¦---|---¦---|---¦---|---¦---|
Experience with thermal feedback	|---¦---|---¦---|---¦---|---¦---|

Please indicate which hand is dominant:

left ☐ right ☐ both ☐

Any comments?

☐

Participant Number: ___________ Instruction Type: ___________

WORKLOAD RATING SCALES

Mental Demand

Low **High**

Physical demand

Low **High**

Time pressure

Low **High**

Effort expended

Low **High**

Performance level achieved

poor **good**

Frustration experienced

Low **High**

Annoyance experienced

Low **High**

Participant Number: ___________ Instruction Type: ___________

Please rate the instruction type you just finished using the following attributes:

	(not at all) 1 2 3 4 5 (much)
Pleasant	|---¦---|---¦---|---¦---|---¦---|
Comfortable	|---¦---|---¦---|---¦---|---¦---|
Disruptive	|---¦---|---¦---|---¦---|---¦---|
Complicated	|---¦---|---¦---|---¦---|---¦---|

Any comments?

Participant Number: ___________ TempLane _End

Please rate how much you liked the different instruction type:

	(not at all) 1 2 3 4 5 (much)
Audio	|---¦---|---¦---|---¦---|---¦---|
Thermal	|---¦---|---¦---|---¦---|---¦---|

Please name reasons for your rating:

Imagine you were presented with thermal feedback on the steering wheel for navigation purposes, where the devices of one side of the wheel will be warmed, while the other side will be cooled, how would you interact:
If the right side of the steering wheel was warmed, while the left side was cooled, I would turn to the:

Left ☐ Right ☐

Is there any other kind of information in a car that you would like to receive through thermal feedback? Why?

At what places in the car would you like to receive thermal feedback?

Any other comments?

A.3 Experiment 2

A.3.1 Experiment 2: Information Sheet

StimLen – Investigating Thermal Feedback for Lane Change Scenarios

GIST Glasgow Interactive Systems Group | University of Glasgow | School of Computing Science

INFORMATION SHEET

BACKGROUND

The goal of this user study is to improve safety in driving situations by providing navigational information through thermal feedback on the steering wheel. To achieve this, we compare different types of stimuli representation.

TASK

The study is conducted in a driving simulator and will consist of eight blocks. You will be asked to follow instructions given through thermal feedback, both warm and cold. You will perform the tasks sitting in a padded chair. There will be a steering wheel securely attached to the desk in front of you. You will be holding the wheel throughout the experiment with one hand while driving. The other hand will be placed on the table next to the steering wheel and you will be asked to place your finger on the Peltier device (used for the thermal feedback). The simulator requires you to keep a virtual vehicle within the limits of the road and keep it inside a lane. You will get instructions to change lanes through thermal feedback (warm for right and cold for left). Please change to the next lane on the indicated side as fast and accurately as possible and try to stay inside the lane, whenever you are not actively changing into another. Please always only change one lane.

You will have time to get used to the simulator and the thermal feedback before the start of the first block of the experiment. Between the blocks you will have time to take a break. After the eight blocks you will be asked to fill in a questionnaire.

INSTRUCTIONS

- Please place one hand on the steering wheel and the other on the table while driving.
- Please try to follow the instructions given by the system to the best of your ability and try to keep inside the lane. If not indicated otherwise, please follow the road straight ahead.

MISCELLANEOUS

- You will be wearing headphones throughout the experiment.
- The experiment is divided into blocks. You can rest between the blocks for as long as you need.
- You can withdraw from the study at any time without penalty. The data recorded until then will be destroyed.

IMPORTANT

The systems you interact with will not ask or store personal information and all data recorded are anonymised. 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. To take part in this study, the following criteria must be met:

- I am at least 18 years old
- I hold a full driving licence
- I have no visual impairments (not including wearing glasses or contact lenses)
- I have no neurological disorders (e.g. epilepsy)
- I do not suffer from motion sickness
- I do not have any sensory impairments

You will be given resting sessions between experimental blocks but please do not be afraid to ask for a break if required at any time during the study. Furthermore, if you feel unwell at any point, please let the experimenter know immediately so that medical attention can be given as soon as possible. If you have any questions about the study or would like more information about our research in general, contact details are provided below.

CONTACT DETAILS

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Supervisor: Professor Stephen Brewster

Email: stephen.brewster@glasgow.ac.uk

Office: Room S131, Sir Alwyn Williams Building (Computing Science), Glasgow, G12 8RZ, Scotland

Tel: +44 (0)141-330-4966

This study has been approved by the Ethics Committee (Reference Number - 300160073).

This research is part funded by the EPSRC and Jaguar Land Rover.

A.3.2 Experiment 2: Consent Form

StimLen – Investigating Thermal Feedback for Lane Change Scenarios

CONSENT FORM

☐ I confirm that I have read and understood the Study Information Sheet provided to me for the above study and have had the opportunity to ask questions.

☐ The study has been explained to me, and I understand the explanation given and what my participation will involve.

☐ I understand that during the course of the study the experimenter will give additional instructions concerning the experiment and that the purpose of some of the instructions will only be explained at the end of the study.

☐ I understand that my participation is voluntary and that I am free to withdraw at any time, without giving a reason.

☐ I understand that the research data may be accessed by researchers working at the GIST, but that at all times my personal data will be kept confidential in accordance with data protection guidelines.

I have initialled the above boxes myself and I agree to take part in the study.

FULL NAME: ____

SIGNATURE: ____

DATE: ____

EMAIL: ____

Experimenter: Ms Patrizia Di Campli San Vito
(p.di-campli-san-vito.1@research.gla.ac.uk)

DATE, SIGNATURE: ____

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 -300160073).

This research is part funded by the EPSRC and Jaguar Land Rover.

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A.3.3 Experiment 2: Questionnaires

QuestionnaireStimLen

At the end

* 1. Participant Number

* 2. Age

* 3. Gender

◯ male ◯ female ◯ other

* 4. Occupation (and field of study, if applicable)

* 5. Years of driving experience

* 6. Country, where the driving license was obtained

* 7. Please indicate which hand is dominant

◯ left ◯ right ◯ both

* 8. Please rate your experience with the following

	1 (none)	2	3	4	5 (very much)
Experience with a driving simulator	◯	◯	◯	◯	◯
Experience with thermal feedback	◯	◯	◯	◯	◯

9. Any comments?

A.4 Experiment 3

A.4.1 Experiment 3: Information Sheet

TempWheel – Investigating Thermal Feedback on the Steering Wheel

GIST Glasgow Interactive Systems Group
University of Glasgow | School of Computing Science

INFORMATION SHEET

BACKGROUND

The goal of this user study is to improve safety in driving situations by providing navigational information through thermal feedback on the steering wheel.

TASK

The study is conducted in a driving simulator and will consist of three blocks. You will be asked to follow instructions given by a navigation system, either through thermal feedback, both warm and cold, or audio instructions. You will perform the tasks sitting in a padded, adjustable chair. There will be a steering wheel securely attached to the desk in front of you. You will be holding the wheel throughout the experiment while driving. The simulator requires you to keep a virtual vehicle within the limits of the road, driving on the right hand side of the road. You will follow navigational instructions by turning on specified points.

You will have time to get used to the simulator and the thermal feedback and the audio navigation in the first block of the experiment. In the second and third block you will be asked to follow instructions given by either an audio or the thermal navigation system. In the beginning and after each block you will be asked to fill in questionnaires and will you have time to take a break.

The navigation instructions will be given in two stages: first you will be given a short indicator 200 metres before the turning point and then another directly before you have to turn. After turning, the virtual car will move to a different location, where you should follow the road straight ahead until the next turning event. The simulation will stop automatically after 12 turns.

INSTRUCTIONS

- Please place both hands at the indicated spaces on the steering wheel while driving.
- Please drive in the rightmost lane and ignore any road signs, including painted arrows or stop signs painted on the road itself.
- Please try to follow the instructions given by the navigation system to the best of your ability and try to keep inside the lane. If not indicated otherwise, please follow the road straight ahead.

MISCELLANEOUS

- You will be wearing headphones throughout the experiment.
- The experiment is divided into blocks. You can rest between the blocks for as long as you need.
- You can withdraw from the study at any time without penalty. The data recorded until then will be destroyed.

Version No. 3 (June 2017)

IMPORTANT

The systems you interact with will not ask or store personal information and all data recorded are anonymised. 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. To take part in this study, the following criteria must be met:

- I am at least 18 years old
- I hold a full driving licence
- I have no visual impairments (not including wearing glasses or contact lenses)
- I have no neurological disorders (e.g. epilepsy)
- I do not suffer from motion sickness
- I do not have any sensory impairments

You will be given resting sessions between experimental conditions but please do not be afraid to ask for a break if required at any time during the study. Furthermore, if you feel unwell at any point, please let the experimenter know immediately so that medical attention can be given as soon as possible If you have any questions about the study or would like more information about our research in general, contact details are provided below.

CONTACT DETAILS

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Office:	Room F131, Sir Alwyn Williams Building (Computing Science), Glasgow, G12 8RZ, Scotland
Tel:	+44 (0)141-330-8430
Supervisor:	Professor Stephen Brewster
Email:	stephen.brewster@glasgow.ac.uk
Office:	Room S131, Sir Alwyn Williams Building (Computing Science), Glasgow, G12 8RZ, Scotland
Tel:	+44 (0)141-330-4966

This study has been approved by the Ethics Committee (Reference Number - D1483958803605).

This research is part funded by the EPSRC and Jaguar Land Rover.

A.4.2 Experiment 3: Consent Form

TempWheel – Investigating Thermal Feedback on the Steering Wheel

CONSENT FORM

- [ ] I confirm that I have read and understood the Study Information Sheet provided to me for the above study and have had the opportunity to ask questions.
- [ ] The study has been explained to me, and I understand the explanation given and what my participation will involve.
- [ ] I understand that during the course of the study the experimenter will give additional instructions concerning the experiment and that the purpose of some of the instructions will only be explained at the end of the study.
- [ ] I understand that my participation is voluntary and that I am free to withdraw at any time, without giving a reason.
- [ ] I understand that the research data may be accessed by researchers working at the GIST, but that at all times my personal data will be kept confidential in accordance with data protection guidelines.

I have initialled the above boxes myself and I agree to take part in the study.

FULL NAME: ____

SIGNATURE: ____

DATE: ____

EMAIL: ____

Experimenter: Ms Patrizia Di Campli San Vito
(p.di-campli-san-vito.1@research.gla.ac.uk)

DATE, SIGNATURE: ____

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 - D1483958803605).

This research is part funded by the EPSRC and Jaguar Land Rover.

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GIST Glasgow Interactive Systems Group

Version No. 2 (March 2017)

A.4.3 Experiment 3: Questionnaires

Participant Number: ___________ TempWheel_Beginning

Age: ___________

Gender: male ☐ female ☐ other ☐

Occupation / field of study: ____

Years of driving experience: ___________

Country, where driving licence was obtained: ____________________

Please rate your experience with the following:

	(none) 1 2 3 4 5 (much)
Experience with a driving simulator	|---¦---|---¦---|---¦---|---¦---|
Experience with audio navigation	|---¦---|---¦---|---¦---|---¦---|
Experience with thermal feedback	|---¦---|---¦---|---¦---|---¦---|

In the following experiment, you will be presented with thermal feedback for navigation purposes on the steering wheel, where the device of one side of the wheel will be warmed, while the other side will be cooled.
Please decide:
If the right side of the steering wheel was warmed, while the left side was cooled, I would turn to the:

Left ☐ Right ☐

Any comments?

Participant Number: ___________ Navigation Type: ___________

WORKLOAD RATING SCALES

Mental Demand

Low High

Physical demand

Low High

Time pressure

Low High

Effort expended

Low High

Performance level achieved

poor good

Frustration experienced

Low High

Annoyance experienced

Low High

Participant Number: ___________ Navigation Type: ___________

Please rate the navigation you just finished using the following attributes:

	(not at all) 1	2	3	4	5 (much)
Pleasant					
Comfortable					
Disruptive					
Complicated					

Any comments?

Participant Number: ___________ TempWheel_End

Please rate how much you liked the different navigation types:

	(not at all) 1	2	3	4	5 (much)
Audio	|---¦---|---¦---|---¦---|---¦---|				
Thermal	|---¦---|---¦---|---¦---|---¦---|				

Please name reasons for your rating:

Having finished the experiment, which direction would you turn towards, if presented with thermal feedback for navigation purposes?

Warm ☐ Cold ☐

Is there any other kind of information in a car that you would like to receive through thermal feedback? Why?

Is there any other place in the car where you would like to receive thermal feedback?

Any other comments?

A.5 Experiment 4

A.5.1 Experiment 4: Information Sheet

HapNav – Investigating Thermal and Cutaneous Push Feedback on the Steering Wheel

INFORMATION SHEET

BACKGROUND

The goal of this user study is to improve safety in driving situations by providing navigational information through thermal feedback on the steering wheel.

TASK

The study is conducted in a driving simulator and will consist of two blocks. You will be asked to follow instructions given by a navigation system, either through thermal feedback (warm temperature change) or cutaneous push (a pin poking your palm gently). You will perform the tasks sitting in a gaming racing chair. There will be a steering wheel securely attached in front of you and foot pedals on the ground. You will be holding the wheel throughout the experiment while driving. The simulator requires you to keep a virtual vehicle within the limits of the road, driving on the right-hand side of the road. You will follow navigational instructions by turning on specified points.

You will have time to get used to the simulator, the thermal feedback and the push feedback. In the first block you will be asked to follow instructions given by either push feedback or thermal, in the second block it will be the other condition. Each block consists of an introduction to the stimuli, a short training period and the task in the assigned condition. In the beginning and after each block you will be asked to fill in questionnaires and will you have time to take a break.

The navigation instructions will be given in two stages: first you will be given a short indicator 200 metres before the turning point and then another directly before you the turn. When you identify the indicator 200 metres before the turn, please press the right or middle foot pedal on the side of the turning direction (for left, please press the middle pedal). At the turning point, please turn towards the indicated direction. After turning, the virtual car will move (reset) to a different location, where you should follow the road straight ahead until the next turning event. The simulation will stop automatically after 12 turns.

INSTRUCTIONS

- Please place both hands at the indicated spaces on the steering wheel while driving.
- Please drive in the rightmost lane and ignore any road signs, including painted arrows or stop signs painted on the road itself.
- Please try to follow the instructions given by the navigation system to the best of your ability and try to keep inside the lane. If not indicated otherwise, please follow the road straight ahead.
- If a resetting error occurs, please wait for the experimenter to reset the car manually.

MISCELLANEOUS

- You will be wearing headphones throughout the experiment.
- The experiment is divided into blocks. You can rest between the blocks for as long as you need.

- You can withdraw from the study at any time without penalty. The data recorded until then will be destroyed.

IMPORTANT

The systems you interact with will not ask or store personal information and all data recorded are anonymised. 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. To take part in this study, the following criteria must be met:

- I am at least 18 years old
- I hold a full driving licence
- I have no visual impairments (not including wearing glasses or contact lenses)
- I have no neurological disorders (e.g. epilepsy)
- I do not suffer from motion sickness
- I do not have any sensory impairments

You will be given resting sessions between experimental conditions but please do not be afraid to ask for a break if required at any time during the study. Furthermore, if you feel unwell at any point, please let the experimenter know immediately so that medical attention can be given as soon as possible If you have any questions about the study or would like more information about our research in general, contact details are provided below.

CONTACT DETAILS

Name:	Patrizia Di Campli San Vito (PhD student/Experimenter)
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Tel:	+44 (0)141-330-4966

This study has been approved by the Ethics Committee (Reference Number - 300160073).

This research is part funded by the EPSRC and Jaguar Land Rover.

A.5.2 Experiment 4: Consent Form

HapNav – Investigating Thermal and Cutaneous Push Feedback on the Steering Wheel

CONSENT FORM

☐ I confirm that I have read and understood the Study Information Sheet provided to me for the above study and have had the opportunity to ask questions.

☐ The study has been explained to me, and I understand the explanation given and what my participation will involve.

☐ I understand that during the course of the study the experimenter will give additional instructions concerning the experiment and that the purpose of some of the instructions will only be explained at the end of the study.

☐ I understand that my participation is voluntary and that I am free to withdraw at any time, without giving a reason.

☐ I understand that the research data may be accessed by researchers working at the GIST, but that at all times my personal data will be kept confidential in accordance with data protection guidelines.

I have initialled the above boxes myself and I agree to take part in the study.

FULL NAME: ____

SIGNATURE: ____

DATE: ____

I want to be added to the participant's pool: ☐ YES ☐ NO

EMAIL: ____

Experimenter: Ms Patrizia Di Campli San Vito
(p.di-campli-san-vito.1@research.gla.ac.uk)

DATE, SIGNATURE: ____

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 - 300160073).

This research is part funded by the EPSRC and Jaguar Land Rover.

University of Glasgow | School of Computing Science   GIST Glasgow Interactive Systems Group

Version No. 1 (May 2018)

A.5.3 Experiment 4: Questionnaires

BeforeQuestionnaire

Fill in before giving to participant!

* 1. Participant Number

HapNav

Workload and Preference 1

* 2. Navigation Type

○ Cutaneous Push

○ Thermal

* 3. Mental demand

How much mental, visual and auditory activity was required? (e.g. thinking, deciding, calculating, listening, scanning, searching)

Low High

* 4. Physical demand

How much physical activity was required? (e.g. pressing, controlling)

Low High

* 5. Time pressure

How much time pressure did you feel because of the rate at which things occurred or the time limit imposed on the task? (e.g. slow, leisurely, rapid, frantic)

Low High

* 6. Effort expended

How hard did you work (mentally and physically) to accomplish your level of performance?

Low High

* 7. Performance level achieved

How successful do you think you were in doing the task set by the experimenter? How satisfied were you with your performance?

Poor Good

* 8. Frustration experienced

How much frustration did you experience? (e.g. were you relaxed, content, stressed, irritated, discouraged)

Low High

* 9. Annoyance experienced

How annoying did you find the system used in the experiment?

Low High

* 10. Please rate the navigation type you just finished for the following attributes

	1 (not at all)	2	3	4	5 (very much)
Pleasant	○	○	○	○	○
Comfortable	○	○	○	○	○
Disruptive	○	○	○	○	○
Complicated	○	○	○	○	○

11. Any comments?

HapNav

Workload and Preference 2

* 12. Navigation Type

- ◯ Cutaneous Push
- ◯ Thermal

* 13. Mental demand

How much mental, visual and auditory activity was required? (e.g. thinking, deciding, calculating, listening, scanning, searching)

Low High

* 14. Physical demand

How much physical activity was required? (e.g. pressing, controlling)

Low High

* 15. Time pressure

How much time pressure did you feel because of the rate at which things occurred or the time limit imposed on the task? (e.g. slow, leisurely, rapid, frantic)

Low High

* 16. Effort expended

How hard did you work (mentally and physically) to accomplish your level of performance?

Low High

* 17. Performance level achieved

How successful do you think you were in doing the task set by the experimenter? How satisfied were you with your performance?

Poor Good

* 18. Frustration experienced

How much frustration did you experience? (e.g. were you relaxed, content, stressed, irritated, discouraged)

Low High

* 19. Annoyance experienced

How annoying did you find the system used in the experiment?

Low High

* 20. Please rate the navigation type you just finished for the following attributes

	1 (not at all)	2	3	4	5 (very much)
Pleasant	◯	◯	◯	◯	◯
Comfortable	◯	◯	◯	◯	◯
Disruptive	◯	◯	◯	◯	◯
Complicated	◯	◯	◯	◯	◯

21. Any comments?

HapNav

Questionnaire End

* 22. Age

* 23. Gender

male female non-binary

* 24. Occupation (and field of study, if applicable)

* 25. Years of driving experience

* 26. Country, where the driving license was obtained

* 27. Please indicate which hand is dominant

left right both

* 28. Please rate your past experience with the following

	1 (none)	2	3	4	5 (very much)
Experience with a driving simulator					
Experience with cutaneous push feedback					
Experience with thermal feedback					

* 29. Please rate how much you liked the cutaneous push navigation

not at all very much

* 30. Please name reasons for your rating

* 31. Please rate how much you liked the thermal navigation

not at all — very much

* 32. Please name reasons for your rating

33. Which feedback type did you prefer?

- Cutaneous Push
- Thermal

* 34. Did associating warm with the direction of turning feel appropriate?

- yes
- no

* 35. Is there any other kind of information in a car that you would like to receive through thermal feedback? Why?

* 36. Is there any other place in the car where you would like to receive thermal feedback?

37. Any other comments?

A.6 Experiment 5

A.6.1 Experiment 5: Information Sheet

VibraTherm – Investigating Thermal and Vibrotactile Feedback on the Steering Wheel

GIST Glasgow Interactive Systems Group | University of Glasgow | School of Computing Science

INFORMATION SHEET

BACKGROUND

The goal of this user study is to improve safety in driving situations by providing warning cues through thermal and/or vibrotactile feedback on the steering wheel.

TASK

The study is conducted in a driving simulator and will consist of two major blocks. You will be asked to rate warnings, given either through thermal feedback, warm or cold, or vibration or a combination of thermal and vibrotactile feedback (bimodal). You will perform the tasks sitting in a gaming racing chair. There will be a steering wheel securely attached in front of you and you will be holding the wheel throughout the experiment. Please position your hands on the indicated location of the steering wheel and keep them on the devices during the rating and driving phases of the experiment. You will be wearing headphones throughout the experiment, either playing white noise or car sounds.

The first block of the experiment consists of subjectively rating presented stimuli. You will be presented with random stimuli. Please rate their urgency by moving the presented slider through turning of the steering wheel. When you have reached your perceived level of urgency, please select it by pressing the one of the two paddles on the steering wheel. There will be 45 stimuli in total. Please let the experimenter know, when you want to take a rest.

The second major block consist of a driving task. The simulator requires you to keep a virtual vehicle within the limits of the road. The car will be placed on a five-lane motorway. You will start in the middle lane and should swiftly and precisely change to another lane, when it is indicated by an arrow on one of the bridges. Please keep then within that lane, until another arrow appears. In between these lane changes you will be presented with urgency warnings, which you should rate swiftly by pressing one of three buttons on the steering wheel. The upper button (Y) should be pressed for warnings of high urgency, the middle button (B) for warnings of medium urgency and the lowest button (A) for warnings of low urgency. There will be a training phase before the main driving task begins. The driving task itself will be separated into five blocks of approximately 5 min each. You can break between these blocks, but please let the experimenter know, if you need to rest within a block.

INSTRUCTIONS

- Please place both hands at the indicated spaces on the steering wheel while driving.
- Please try to follow the instructions given by the arrows on the bridges to the best of your ability and try to keep inside the lane.

MISCELLANEOUS

- You will be wearing headphones throughout the experiment.

- The experiment is divided into blocks. You can rest between the blocks for as long as you need. If additional breaks are required, please let the experimenter know.
- You can withdraw from the study at any time without penalty. The data recorded until then will be destroyed.

IMPORTANT

The systems you interact with will not ask or store personal information and all data recorded are anonymised. 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. To take part in this study, the following criteria must be met:

- I am at least 18 years old
- I hold a full driving licence
- I have no visual impairments (not including wearing glasses or contact lenses)
- I have no neurological disorders (e.g. epilepsy)
- I do not suffer from motion sickness
- I do not have any sensory impairments

You will be given resting sessions between experimental conditions but please do not be afraid to ask for a break if required at any time during the study. Furthermore, if you feel unwell at any point, please let the experimenter know immediately so that medical attention can be given as soon as possible. Should you have any questions about the study or like more information about our research in general, contact details are provided below.

CONTACT DETAILS

Name:	Patrizia Di Campli San Vito (PhD student/Experimenter)
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Supervisor:	Professor Stephen Brewster
Email:	stephen.brewster@glasgow.ac.uk
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Tel:	+44 (0)141-330-4966

This study has been approved by the Ethics Committee (Reference Number - 300160073).

This research is part funded by the EPSRC and Jaguar Land Rover.

A.6.2 Experiment 5: Consent Form

VibraTherm – Investigating Thermal and Vibrotactile Feedback on the Steering Wheel

CONSENT FORM

- ☐ I confirm that I have read and understood the Study Information Sheet provided to me for the above study and have had the opportunity to ask questions.
- ☐ The study has been explained to me, and I understand the explanation given and what my participation will involve.
- ☐ I understand that during the course of the study the experimenter will give additional instructions concerning the experiment and that the purpose of some of the instructions will only be explained at the end of the study.
- ☐ I understand that my participation is voluntary and that I am free to withdraw at any time, without giving a reason.
- ☐ I understand that the research data may be accessed by researchers working at the GIST, but that at all times my personal data will be kept confidential in accordance with data protection guidelines.

I have initialled the above boxes myself and I agree to take part in the study.

FULL NAME: ____

SIGNATURE: ____

DATE: ____

I want to be added to the participant's pool: ☐ YES ☐ NO

EMAIL: ____

Experimenter: Ms Patrizia Di Campli San Vito
(p.di-campli-san-vito.1@research.gla.ac.uk)

DATE, SIGNATURE: ____

Supervisor details: Professor Stephen Brewster
(stephen.brewster.glasgow.gla.ac.uk, 0141-330-4966)

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GIST Glasgow Interactive Systems Group

A.6.3 Experiment 5: Questionnaires

VibraTherm

QuestionnaireVibraTherm

* 1. Participant Number

* 2. Age

* 3. Gender

male female non-binary

* 4. Occupation (and field of study, if applicable)

* 5. Years of driving experience

* 6. Country, where the driving license was obtained

* 7. Please indicate which hand is dominant

left right both

* 8. Please rate how much experience you had with the following prior to the experiment:

	1 (none)	2	3	4	5 (very much)
Experience with a driving simulator					
Experience with vibrotactile feedback					
Experience with thermal feedback					

9. Please indicate your preference for the different feedback types by ranking them from most preferred (1) to least preferred (3).

[ ]	Thermal feedback
[ ]	Vibrotactile feedback
[ ]	Bimodal feedback

* 10. Please name reasons for your rating

[ ]

* 11. Which feedback type felt most **urgent**?

○ thermal ○ vibrotactile ○ bimodal (thermal and vibrotactile together) ○ all equally

* 12. Which feedback type felt most **comfortable**?

○ thermal ○ vibrotactile ○ bimodal (thermal and vibrotactile together) ○ all equally

* 13. Which direction of temperature felt more **urgent**?

○ warm ○ cold ○ both equally

* 14. Which direction of temperature felt more **comfortable**?

○ warm ○ cold ○ both equally

15. Any comments?

[ ]

A.6.4 Experiment 5: Statistics of Subjective Ratings with *0* Ratings Included

Experiment 5: Statistics of Independent Variables

Urgency	Modality	Urgency: Modality
$F(2,27) = 23.35$ **$p < 0.0001$***	$F(4,61) = 135.13$ **$p < 0.001$***	$F(8,127) = 2.20$ **$p = 0.003$***

Table A.1: Experiment 5: Statistics for the Subjective Ratings including *0* Ratings; significant results are bold and marked with an asterisk.

Experiment 5: Statistics of *post hoc* tests for Urgency for Subjective Ratings with *0* ratings included

Urgency - Urgency	*t(27)*	*p*
Low - Medium	3.33	**0.007***
Low - Urgent	6.05	< **0.0001***
Medium - Urgent	2.38	0.06

Table A.2: Experiment 5: Statistics of *post hoc* test results for Urgency for Subjective Ratings with *0*; significant results are bold and marked with an asterisk.

Experiment 5: Statistics of *post hoc* tests for Modality for Subjective Ratings with *0* ratings included

Modality - Modality	*t(61)*	*p*
Bimodal Cold - Bimodal Warm	1.30	0.69
Bimodal Cold - Thermal Cold	14.79	< **0.0001***
Bimodal Cold - Thermal Warm	13.70	< **0.0001***
Bimodal Cold - Vibration	0.66	0.96
Bimodal Warm - Thermal Cold	15.78	< **0.0001***
Bimodal Warm - Thermal Warm	14.69	< **0.0001***
Bimodal Warm - Vibration	0.65	0.97
Thermal Cold - Thermal Warm	0.80	0.93
Thermal Cold - Vibration	15.45	< **0.0001***
Thermal Warm - Vibration	14.35	< **0.0001***

Table A.3: Experiment 5: Statistics of *post hoc* test results for Modality for Subjective Ratings with *0*; significant results are bold and marked with an asterisk.

Experiment 5: Statistics of *post hoc* tests for the Interaction between Urgency and Modality for Subjective Ratings with *0* ratings included

Urgency,Modality - Urgency,Modality	*t*	*p*
Low,Bimodal Cold - Medium,Bimodal Cold	*t(134)* = 1.61	0.95
Low,Bimodal Cold - Urgent,Bimodal Cold	*t(139)* = 1.71	0.93
Low,Bimodal Cold - Low,Bimodal Warm	*t(132)* = 0.21	1.00
Low,Bimodal Cold - Medium,Bimodal Warm	*t(140)* = 2.51	0.44
Low,Bimodal Cold - Urgent,Bimodal Warm	*t(139)* = 2.79	0.26
Low,Bimodal Cold - Low,Thermal Cold	*t(135)* = 12.08	$<$ **0.0001***
Low,Bimodal Cold - Medium,Thermal Cold	*t(142)* = 10.10	$<$ **0.0001***
Low,Bimodal Cold - Urgent,Thermal Cold	*t(141)* = 9.24	$<$ **0.0001***
Low,Bimodal Cold - Low,Thermal Warm	*t(132)* = 12.05	$<$ **0.0001***
Low,Bimodal Cold - Medium,Thermal Warm	*t(139)* = 10.45	$<$ **0.0001***
Low,Bimodal Cold - Urgent,Thermal Warm	*t(138)* = 6.78	$<$ **0.0001***
Low,Bimodal Cold - Low,Vibration	*t(134)* = 0.46	1.00
Low,Bimodal Cold - Medium,Vibration	*t(140)* = 1.68	0.94
Low,Bimodal Cold - Urgent,Vibration	*t(139)* = 1.95	0.83
Medium,Bimodal Cold - Urgent,Bimodal Cold	*t(130)* = 0.07	1.00
Medium,Bimodal Cold - Low,Bimodal Warm	*t(139)* = 1.04	1.00
Medium,Bimodal Cold - Medium,Bimodal Warm	*t(131)* = 1.35	0.99
Medium,Bimodal Cold - Urgent,Bimodal Warm	*t(138)* = 1.53	0.97
Medium,Bimodal Cold - Low,Thermal Cold	*t(140)* = 1.53	$<$ **0.0001***
Medium,Bimodal Cold - Medium,Thermal Cold	*t(135)* = 11.90	$<$ **0.0001***
Medium,Bimodal Cold - Urgent,Thermal Cold	*t(140)* = 10.39	$<$ **0.0001***
Medium,Bimodal Cold - Low,Thermal Warm	*t(138)* = 12.79	$<$ **0.0001***
Medium,Bimodal Cold - Medium,Thermal Warm	*t(130)* = 12.28	$<$ **0.0001***
Medium,Bimodal Cold - Urgent,Thermal Warm	*t(138)* = 7.93	$<$ **0.0001***
Medium,Bimodal Cold - Low,Vibration	*t(140)* = 0.81	1.00
Medium,Bimodal Cold - Medium,Vibration	*t(130)* = 0.46	1.00
Medium,Bimodal Cold - Urgent,Vibration	*t(134)* = 0.68	1.00

Table A.4: Experiment 5: Part 1 Statistics of *post hoc* tests for the Interaction between Urgency and Modality for Subjective Ratings with *0* ratings included; significant results are bold and marked with an asterisk.

Urgency,Modality - Urgency,Modality	*t*	*p*
Urgent,Bimodal Cold - Low,Bimodal Warm	$t(134) = 1.10$	1.00
Urgent,Bimodal Cold - Medium,Bimodal Warm	$t(134) = 1.23$	1.00
Urgent,Bimodal Cold - Urgent,Bimodal Warm	$t(129) = 1.56$	0.96
Urgent,Bimodal Cold - Low,Thermal Cold	$t(140) = 12.99$	< **0.0001***
Urgent,Bimodal Cold - Medium,Thermal Cold	$t(141) = 11.38$	< **0.0001***
Urgent,Bimodal Cold - Urgent,Thermal Cold	$t(133) = 11.00$	< **0.0001***
Urgent,Bimodal Cold - Low,Thermal Warm	$t(138) = 12.96$	< **0.0001***
Urgent,Bimodal Cold - Medium,Thermal Warm	$t(139) = 11.70$	< **0.0001***
Urgent,Bimodal Cold - Urgent,Thermal Warm	$t(129) = 8.42$	< **0.0001***
Urgent,Bimodal Cold - Low,Vibration	$t(139) = 0.87$	1.00
Urgent,Bimodal Cold - Medium,Vibration	$t(139) = 0.38$	1.00
Urgent,Bimodal Cold - Urgent,Vibration	$t(130) = 0.66$	1.00
Low,Bimodal Warm - Medium,Bimodal Warm	$t(136) = 2.97$	0.18
Low,Bimodal Warm - Urgent,Bimodal Warm	$t(139) = 3.39$	0.06
Low,Bimodal Warm - Low,Thermal Cold	$t(133) = 12.11$	< **0.0001***
Low,Bimodal Warm - Medium,Thermal Cold	$t(140) = 10.19$	< **0.0001***
Low,Bimodal Warm - Urgent,Thermal Cold	$t(139) = 9.32$	< **0.0001***
Low,Bimodal Warm - Low,Thermal Warm	$t(130) = 12.08$	< **0.0001***
Low,Bimodal Warm - Medium,Thermal Warm	$t(137) = 10.53$	< **0.0001***
Low,Bimodal Warm - Urgent,Thermal Warm	$t(136) = 6.88$	< **0.0001***
Low,Bimodal Warm - Low,Vibration	$t(133) = 0.25$	1.00
Low,Bimodal Warm - Medium,Vibration	$t(139) = 1.47$	0.98
Low,Bimodal Warm - Urgent,Vibration	$t(139) = 1.73$	0.92
Medium,Bimodal Warm - Urgent,Bimodal Warm	$t(132) = 0.32$	1.00
Medium,Bimodal Warm - Low,Thermal Cold	$t(139) = 13.92$	< **0.0001***
Medium,Bimodal Warm - Medium,Thermal Cold	$t(134) = 12.99$	< **0.0001***
Medium,Bimodal Warm - Urgent,Thermal Cold	$t(139) = 11.51$	< **0.0001***
Medium,Bimodal Warm - Low,Thermal Warm	$t(137) = 13.87$	< **0.0001***
Medium,Bimodal Warm - Medium,Thermal Warm	$t(130) = 13.35$	< **0.0001***
Medium,Bimodal Warm - Urgent,Thermal Warm	$t(137) = 9.07$	< **0.0001***
Medium,Bimodal Warm - Low,Vibration	$t(140) = 2.07$	0.75
Medium,Bimodal Warm - Medium,Vibration	$t(131) = 0.90$	1.00
Medium,Bimodal Warm - Urgent,Vibration	$t(139) = 0.61$	1.00
Urgent,Bimodal Warm - Low,Thermal Cold	$t(139) = 14.29$	< **0.0001***
Urgent,Bimodal Warm - Medium,Thermal Cold	$t(139) = 12.71$	< **0.0001***
Urgent,Bimodal Warm - Urgent,Thermal Cold	$t(131) = 12.38$	< **0.0001***
Urgent,Bimodal Warm - Low,Thermal Warm	$t(136) = 14.24$	< **0.0001***
Urgent,Bimodal Warm - Medium,Thermal Warm	$t(137) = 13.01$	< **0.0001***
Urgent,Bimodal Warm - Urgent,Thermal Warm	$t(127) = 9.83$	< **0.0001***
Urgent,Bimodal Warm - Low,Vibration	$t(138) = 2.35$	0.55
Urgent,Bimodal Warm - Medium,Vibration	$t(139) = 1.10$	1.00
Urgent,Bimodal Warm - Urgent,Vibration	$t(130) = 0.90$	1.00

Table A.5: Experiment 5: Part 2 of Statistics of *post hoc* tests for the Interaction between Urgency and Modality for Subjective Ratings with *0* ratings included; significant results are bold and marked with an asterisk.

Urgency,Modality - Urgency,Modality	*t(229)*	*p*
Low,Thermal Cold - Medium,Thermal Cold	*t(137)* = 1.79	0.90
Low,Thermal Cold - Urgent,Thermal Cold	*t(140)* = 3.12	0.13
Low,Thermal Cold - Low,Thermal Warm	*t(133)* = 0.12	1.00
Low,Thermal Cold - Medium,Thermal Warm	*t(140)* = 0.96	1.00
Low,Thermal Cold - Urgent,Thermal Warm	*t(139)* = 4.77	**0.0004***
Low,Thermal Cold - Low,Vibration	*t(134)* = 12.54	< **0.0001***
Low,Thermal Cold - Medium,Vibration	*t(140)* = 13.25	< **0.0001***
Low,Thermal Cold - Urgent,Vibration	*t(140)* = 13.62	< **0.0001***
Medium,Thermal Cold - Urgent,Thermal Cold	*t(135)* = 1.23	1.00
Medium,Thermal Cold - Low,Thermal Warm	*t(141)* = 1.51	0.97
Medium,Thermal Cold - Medium,Thermal Warm	*t(135)* = 0.45	1.00
Medium,Thermal Cold - Urgent,Thermal Warm	*t(139)* = 3.31	0.08
Medium,Thermal Cold - Low,Vibration	*t(143)* = 10.54	< **0.0001***
Medium,Thermal Cold - Medium,Vibration	*t(135)* = 12.35	< **0.0001***
Medium,Thermal Cold - Urgent,Vibration	*t(141)* = 12.00	< **0.0001***
Urgent,Thermal Cold - Low,Thermal Warm	*t(140)* = 2.49	0.45
Urgent,Thermal Cold - Medium,Thermal Warm	*t(139)* = 1.39	0.99
Urgent,Thermal Cold - Urgent,Thermal Warm	*t(131)* = 2.48	0.46
Urgent,Thermal Cold - Low,Vibration	*t(141)* = 9.68	< **0.0001***
Urgent,Thermal Cold - Medium,Vibration	*t(140)* = 10.83	< **0.0001***
Urgent,Thermal Cold - Urgent,Vibration	*t(133)* = 11.66	< **0.0001***
Low,Thermal Warm - Medium,Thermal Warm	*t(137)* = 1.38	0.99
Low,Thermal Warm - Urgent,Thermal Warm	*t(139)* = 6.42	< **0.0001***
Low,Thermal Warm - Low,Vibration	*t(132)* = 12.51	< **0.0001***
Low,Thermal Warm - Medium,Vibration	*t(138)* = 13.21	< **0.0001***
Low,Thermal Warm - Urgent,Vibration	*t(138)* = 13.58	< **0.0001***
Medium,Thermal Warm - Urgent,Thermal Warm	*t(132)* = 4.89	**0.0003***
Medium,Thermal Warm - Low,Vibration	*t(139)* = 10.89	< **0.0001***
Medium,Thermal Warm - Medium,Vibration	*t(130)* = 12.72	< **0.0001***
Medium,Thermal Warm - Urgent,Vibration	*t(139)* = 12.31	< **0.0001***
Urgent,Thermal Warm - Low,Vibration	*t(138)* = 7.21	< **0.0001***
Urgent,Thermal Warm - Medium,Vibration	*t(138)* = 8.35	< **0.0001***
Urgent,Thermal Warm - Urgent,Vibration	*t(129)* = 9.08	< **0.0001***
Low,Vibration - Medium,Vibration	*t(134)* = 1.59	0.96
Low,Vibration - Urgent,Vibration	*t(139)* = 1.94	0.83
Medium,Vibration - Urgent,Vibration	*t(130)* = 0.32	1.00

Table A.6: Experiment 5: Part 3 of Statistics of *post hoc* tests for the Interaction between Urgency and Modality for Subjective Ratings with *0* ratings included; significant results are bold and marked with an asterisk.

A.6.5 Experiment 5: Statistics of *post hoc* tests for the Interaction between Urgency and Modality for Subjective Ratings without *0* ratings; significant results and discussion can be found in section 5.2.6

Urgency,Modality - Urgency,Modality	t	p
Low,Bimodal Cold - Medium,Bimodal Cold	*t(138)* = 0.60	1.00
Low,Bimodal Cold - Urgent,Bimodal Cold	*t(140)* = 0.81	1.00
Low,Bimodal Cold - Low,Bimodal Warm	*t(125)* = 0.24	1.00
Low,Bimodal Cold - Medium,Bimodal Warm	*t(136)* = 1.79	0.90
Low,Bimodal Cold - Urgent,Bimodal Warm	*t(133)* = 2.16	0.69
Low,Bimodal Cold - Low,Thermal Cold	*t(127)* = 11.28	< **0.0001***
Low,Bimodal Cold - Medium,Thermal Cold	*t(129)* = 9.34	< **0.0001***
Low,Bimodal Cold - Urgent,Thermal Cold	*t(124)* = 8.62	< **0.0001***
Low,Bimodal Cold - Low,Thermal Warm	*t(124)* = 9.48	< **0.0001***
Low,Bimodal Cold - Medium,Thermal Warm	*t(129)* = 9.72	< **0.0001***
Low,Bimodal Cold - Urgent,Thermal Warm	*t(125)* = 5.90	< **0.0001***
Low,Bimodal Cold - Low,Vibration	*t(127)* = 0.52	1.00
Low,Bimodal Cold - Medium,Vibration	*t(135)* = 0.86	1.00
Low,Bimodal Cold - Urgent,Vibration	*t(132)* = 1.22	1.00
Medium,Bimodal Cold - Urgent,Bimodal Cold	*t(139)* = 0.20	1.00
Medium,Bimodal Cold - Low,Bimodal Warm	*t(135)* = 0.22	1.00
Medium,Bimodal Cold - Medium,Bimodal Warm	*t(124)* = 1.38	0.99
Medium,Bimodal Cold - Urgent,Bimodal Warm	*t(131)* = 1.71	0.93
Medium,Bimodal Cold - Low,Thermal Cold	*t(129)* = 11.65	< **0.0001***
Medium,Bimodal Cold - Medium,Thermal Cold	*t(124)* = 9.91	< **0.0001***
Medium,Bimodal Cold - Urgent,Thermal Cold	*t(125)* = 9.03	< **0.0001***
Medium,Bimodal Cold - Low,Thermal Warm	*t(128)* = 9.81	< **0.0001***
Medium,Bimodal Cold - Medium,Thermal Warm	*t(124)* = 10.28	< **0.0001***
Medium,Bimodal Cold - Urgent,Thermal Warm	*t(123)* = 6.36	< **0.0001***
Medium,Bimodal Cold - Low,Vibration	*t(135)* = 0.05	1.00
Medium,Bimodal Cold - Medium,Vibration	*t(123)* = 0.43	1.00
Medium,Bimodal Cold - Urgent,Vibration	*t(133)* = 0.75	1.00

Table A.7: Experiment 5: Part 1 Statistics of *post hoc* tests for the Interaction between Urgency and Modality for Subjective Ratings without *0* ratings included; significant results are bold and marked with an asterisk.

Urgency,Modality - Urgency,Modality	t	p
Urgent,Bimodal Cold - Low,Bimodal Warm	$t(132) = 0.36$	1.00
Urgent,Bimodal Cold - Medium,Bimodal Warm	$t(132) = 1.21$	1.00
Urgent,Bimodal Cold - Urgent,Bimodal Warm	$t(123) = 1.61$	0.95
Urgent,Bimodal Cold - Low,Thermal Cold	$t(128) = 11.86$	$<$ **0.0001***
Urgent,Bimodal Cold - Medium,Thermal Cold	$t(128) = 9.98$	$<$ **0.0001***
Urgent,Bimodal Cold - Urgent,Thermal Cold	$t(120) = 9.29$	$<$ **0.0001***
Urgent,Bimodal Cold - Low,Thermal Warm	$t(127) = 10.00$	$<$ **0.0001***
Urgent,Bimodal Cold - Medium,Thermal Warm	$t(128) = 10.35$	$<$ **0.0001***
Urgent,Bimodal Cold - Urgent,Thermal Warm	$t(118) = 6.59$	$<$ **0.0001***
Urgent,Bimodal Cold - Low,Vibration	$t(132) = 0.09$	1.00
Urgent,Bimodal Cold - Medium,Vibration	$t(132) = 0.27$	1.00
Urgent,Bimodal Cold - Urgent,Vibration	$t(123) = 0.63$	1.00
Low,Bimodal Warm - Medium,Bimodal Warm	$t(138) = 2.05$	0.77
Low,Bimodal Warm - Urgent,Bimodal Warm	$t(140) = 2.59$	0.38
Low,Bimodal Warm - Low,Thermal Cold	$t(127) = 11.48$	$<$ **0.0001***
Low,Bimodal Warm - Medium,Thermal Cold	$t(128) = 9.56$	$<$ **0.0001***
Low,Bimodal Warm - Urgent,Thermal Cold	$t(125) = 8.81$	$<$ **0.0001***
Low,Bimodal Warm - Low,Thermal Warm	$t(123) = 9.66$	$<$ **0.0001***
Low,Bimodal Warm - Medium,Thermal Warm	$t(128) = 9.90$	$<$ **0.0001***
Low,Bimodal Warm - Urgent,Thermal Warm	$t(125) = 6.10$	$<$ **0.0001***
Low,Bimodal Warm - Low,Vibration	$t(126) = 0.28$	1.00
Low,Bimodal Warm - Medium,Vibration	$t(134) = 0.62$	1.00
Low,Bimodal Warm - Urgent,Vibration	$t(132) = 0.97$	1.00
Medium,Bimodal Warm - Urgent,Bimodal Warm	$t(140) = 0.47$	1.00
Medium,Bimodal Warm - Low,Thermal Cold	$t(130) = 12.86$	$<$ **0.0001***
Medium,Bimodal Warm - Medium,Thermal Cold	$t(125) = 11.11$	$<$ **0.0001***
Medium,Bimodal Warm - Urgent,Thermal Cold	$t(125) = 10.29$	$<$ **0.0001***
Medium,Bimodal Warm - Low,Thermal Warm	$t(128) = 11.02$	$<$ **0.0001***
Medium,Bimodal Warm - Medium,Thermal Warm	$t(124) = 11.48$	$<$ **0.0001***
Medium,Bimodal Warm - Urgent,Thermal Warm	$t(124) = 7.59$	$<$ **0.0001***
Medium,Bimodal Warm - Low,Vibration	$t(136) = 1.28$	0.99
Medium,Bimodal Warm - Medium,Vibration	$t(124) = 0.97$	1.00
Medium,Bimodal Warm - Urgent,Vibration	$t(133) = 0.60$	1.00
Urgent,Bimodal Warm - Low,Thermal Cold	$t(128) = 13.28$	$<$ **0.0001***
Urgent,Bimodal Warm - Medium,Thermal Cold	$t(127) = 11.43$	$<$ **0.0001***
Urgent,Bimodal Warm - Urgent,Thermal Cold	$t(120) = 10.74$	$<$ **0.0001***
Urgent,Bimodal Warm - Low,Thermal Warm	$t(127) = 11.41$	$<$ **0.0001***
Urgent,Bimodal Warm - Medium,Thermal Warm	$t(127) = 11.76$	$<$ **0.0001***
Urgent,Bimodal Warm - Urgent,Thermal Warm	$t(118) = 8.06$	$<$ **0.0001***
Urgent,Bimodal Warm - Low,Vibration	$t(132) = 1.65$	0.94
Urgent,Bimodal Warm - Medium,Vibration	$t(132) = 1.30$	0.99
Urgent,Bimodal Warm - Urgent,Vibration	$t(124) = 0.98$	1.00

Table A.8: Experiment 5: Part 2 of Statistics of *post hoc* tests for the Interaction between Urgency and Modality for Subjective Ratings without *0* ratings included; significant results are bold and marked with an asterisk.

Urgency,Modality - Urgency,Modality	*t*	*p*
Low,Thermal Cold - Medium,Thermal Cold	*t(143)* = 2.38	0.54
Low,Thermal Cold - Urgent,Thermal Cold	*t(143)* = 3.67	**0.03***
Low,Thermal Cold - Low,Thermal Warm	*t(125)* = 1.81	0.89
Low,Thermal Cold - Medium,Thermal Warm	*t(124)* = 1.47	0.98
Low,Thermal Cold - Urgent,Thermal Warm	*t(122)* = 5.19	**0.0001***
Low,Thermal Cold - Low,Vibration	*t(127)* = 11.76	< **0.0001***
Low,Thermal Cold - Medium,Vibration	*t(129)* = 12.05	< **0.0001***
Low,Thermal Cold - Urgent,Vibration	*t(128)* = 12.43	< **0.0001***
Medium,Thermal Cold - Urgent,Thermal Cold	*t(142)* = 1.18	1.00
Medium,Thermal Cold - Low,Thermal Warm	*t(122)* = 0.04	1.00
Medium,Thermal Cold - Medium,Thermal Warm	*t(124)* = 0.31	1.00
Medium,Thermal Cold - Urgent,Thermal Warm	*t(121)* = 3.40	0.06
Medium,Thermal Cold - Low,Vibration	*t(129)* = 9.84	< **0.0001***
Medium,Thermal Cold - Medium,Vibration	*t(124)* = 10.30	< **0.0001***
Medium,Thermal Cold - Urgent,Vibration	*t(128)* = 10.54	< **0.0001***
Urgent,Thermal Cold - Low,Thermal Warm	*t(121)* = 0.79	1.00
Urgent,Thermal Cold - Medium,Thermal Warm	*t(121)* = 1.14	1.00
Urgent,Thermal Cold - Urgent,Thermal Warm	*t(116)* = 2.60	0.38
Urgent,Thermal Cold - Low,Vibration	*t(125)* = 9.09	< **0.0001***
Urgent,Thermal Cold - Medium,Vibration	*t(125)* = 9.43	< **0.0001***
Urgent,Thermal Cold - Urgent,Vibration	*t(120)* = 9.88	< **0.0001***
Low,Thermal Warm - Medium,Thermal Warm	*t(142)* = 0.47	1.00
Low,Thermal Warm - Urgent,Thermal Warm	*t(142)* = 4.88	**0.0003***
Low,Thermal Warm - Low,Vibration	*t(125)* = 10.09	< **0.0001***
Low,Thermal Warm - Medium,Vibration	*t(130)* = 10.27	< **0.0001***
Low,Thermal Warm - Urgent,Vibration	*t(129)* = 10.65	< **0.0001***
Medium,Thermal Warm - Urgent,Thermal Warm	*t(142)* = 5.32	< **0.0001***
Medium,Thermal Warm - Low,Vibration	*t(132)* = 10.25	< **0.0001***
Medium,Thermal Warm - Medium,Vibration	*t(125)* = 10.78	< **0.0001***
Medium,Thermal Warm - Urgent,Vibration	*t(129)* = 11.03	< **0.0001***
Urgent,Thermal Warm - Low,Vibration	*t(127)* = 6.44	< **0.0001***
Urgent,Thermal Warm - Medium,Vibration	*t(125)* = 6.81	< **0.0001***
Urgent,Thermal Warm - Urgent,Vibration	*t(120)* = 7.24	< **0.0001***
Low,Vibration - Medium,Vibration	*t(138)* = 0.47	1.00
Low,Vibration - Urgent,Vibration	*t(140)* = 0.94	1.00
Medium,Vibration - Urgent,Vibration	*t(139)* = 0.47	1.00

Table A.9: Experiment 5: Part 3 of Statistics of *post hoc* tests for the Interaction between Urgency and Modality for Subjective Ratings without *0* ratings included; significant results are bold and marked with an asterisk.

A.6.6 Experiment 5: Statistics of *post hoc* tests for the Interaction between Urgency and Modality for for Missed Stimuli (*0* Ratings) of the Subjective Rating; significant results and discussion can be found in section 5.2.6

Urgency,Modality - Urgency,Modality	*t*	*p*
Low,Bimodal Cold - Medium,Bimodal Cold	*t(170)* = 0.00	1.00
Low,Bimodal Cold - Urgent,Bimodal Cold	*t(170)* = 0.00	1.00
Low,Bimodal Cold - Low,Bimodal Warm	*t(127)* = 0.28	1.00
Low,Bimodal Cold - Medium,Bimodal Warm	*t(128)* = 0.00	1.00
Low,Bimodal Cold - Urgent,Bimodal Warm	*t(128)* = 0.00	1.00
Low,Bimodal Cold - Low,Thermal Cold	*t(127)* = 6.36	<**0.0001***
Low,Bimodal Cold - Medium,Thermal Cold	*t(128)* = 4.44	**0.002***
Low,Bimodal Cold - Urgent,Thermal Cold	*t(128)* = 3.61	**0.03***
Low,Bimodal Cold - Low,Thermal Warm	*t(127)* = 6.36	<**0.0001***
Low,Bimodal Cold - Medium,Thermal Warm	*t(128)* = 6.66	<**0.0001***
Low,Bimodal Cold - Urgent,Thermal Warm	*t(128)* = 2.22	0.65
Low,Bimodal Cold - Low,Vibration	*t(127)* = 0.00	1.00
Low,Bimodal Cold - Medium,Vibration	*t(128)* = 0.00	1.00
Low,Bimodal Cold - Urgent,Vibration	*t(128)* = 0.00	1.00
Medium,Bimodal Cold - Urgent,Bimodal Cold	*t(170)* = 0.00	1.00
Medium,Bimodal Cold - Low,Bimodal Warm	*t(128)* = 0.28	1.00
Medium,Bimodal Cold - Medium,Bimodal Warm	*t(127)* = 0.00	1.00
Medium,Bimodal Cold - Urgent,Bimodal Warm	*t(128)* = 0.00	1.00
Medium,Bimodal Cold - Low,Thermal Cold	*t(128)* = 6.38	<**0.0001***
Medium,Bimodal Cold - Medium,Thermal Cold	*t(127)* = 4.43	**0.002***
Medium,Bimodal Cold - Urgent,Thermal Cold	*t(128)* = 3.61	**0.03***
Medium,Bimodal Cold - Low,Thermal Warm	*t(128)* = 6.38	<**0.0001***
Medium,Bimodal Cold - Medium,Thermal Warm	*t(127)* = 6.64	<**0.0001***
Medium,Bimodal Cold - Urgent,Thermal Warm	*t(128)* = 2.22	0.65
Medium,Bimodal Cold - Low,Vibration	*t(128)* = 0.00	1.00
Medium,Bimodal Cold - Medium,Vibration	*t(127)* = 0.00	1.00
Medium,Bimodal Cold - Urgent,Vibration	*t(128)* = 0.00	1.00

Table A.10: Experiment 5: Part 1 of Statistics of *post hoc* tests for the Interaction between Urgency and Modality for Missed Stimuli (*0* Ratings) of the Subjective Rating; significant results are bold and marked with an asterisk.

Urgency,Modality - Urgency,Modality	*t*	*p*
Urgent,Bimodal Cold - Low,Bimodal Warm	$t(128) = 0.28$	1.00
Urgent,Bimodal Cold - Medium,Bimodal Warm	$t(128) = 0.00$	1.00
Urgent,Bimodal Cold - Urgent,Bimodal Warm	$t(127) = 0.00$	1.00
Urgent,Bimodal Cold - Low,Thermal Cold	$t(128) = 6.38$	**<0.0001***
Urgent,Bimodal Cold - Medium,Thermal Cold	$t(128) = 4.44$	**0.002***
Urgent,Bimodal Cold - Urgent,Thermal Cold	$t(127) = 3.60$	**0.03***
Urgent,Bimodal Cold - Low,Thermal Warm	$t(128) = 6.38$	**<0.0001***
Urgent,Bimodal Cold - Medium,Thermal Warm	$t(128) = 6.66$	**<0.0001***
Urgent,Bimodal Cold - Urgent,Thermal Warm	$t(127) = 2.21$	0.66
Urgent,Bimodal Cold - Low,Vibration	$t(128) = 0.00$	1.00
Urgent,Bimodal Cold - Medium,Vibration	$t(128) = 0.00$	1.00
Urgent,Bimodal Cold - Urgent,Vibration	$t(127) = 0.00$	1.00
Low,Bimodal Warm - Medium,Bimodal Warm	$t(170) = 0.42$	1.00
Low,Bimodal Warm - Urgent,Bimodal Warm	$t(170) = 0.42$	1.00
Low,Bimodal Warm - Low,Thermal Cold	$t(128) = 6.10$	**<0.0001***
Low,Bimodal Warm - Medium,Thermal Cold	$t(128) = 4.16$	**0.005***
Low,Bimodal Warm - Urgent,Thermal Cold	$t(128) = 3.33$	0.07
Low,Bimodal Warm - Low,Thermal Warm	$t(127) = 6.10$	**<0.0001***
Low,Bimodal Warm - Medium,Thermal Warm	$t(128) = 6.38$	**<0.0001***
Low,Bimodal Warm - Urgent,Thermal Warm	$t(128) = 1.94$	0.83
Low,Bimodal Warm - Low,Vibration	$t(127) = 0.28$	1.00
Low,Bimodal Warm - Medium,Vibration	$t(128) = 0.28$	1.00
Low,Bimodal Warm - Urgent,Vibration	$t(128) = 0.28$	1.00
Medium,Bimodal Warm - Urgent,Bimodal Warm	$t(170) = 0.00$	1.00
Medium,Bimodal Warm - Low,Thermal Cold	$t(128) = 6.38$	**<0.0001***
Medium,Bimodal Warm - Medium,Thermal Cold	$t(127) = 4.43$	**0.002***
Medium,Bimodal Warm - Urgent,Thermal Cold	$t(128) = 3.61$	**0.03***
Medium,Bimodal Warm - Low,Thermal Warm	$t(128) = 6.38$	**<0.0001***
Medium,Bimodal Warm - Medium,Thermal Warm	$t(128) = 6.64$	**<0.0001***
Medium,Bimodal Warm - Urgent,Thermal Warm	$t(128) = 2.22$	0.65
Medium,Bimodal Warm - Low,Vibration	$t(128) = 0.00$	1.00
Medium,Bimodal Warm - Medium,Vibration	$t(127) = 0.00$	1.00
Medium,Bimodal Warm - Urgent,Vibration	$t(128) = 0.00$	1.00
Urgent,Bimodal Warm - Low,Thermal Cold	$t(128) = 6.38$	**<0.0001***
Urgent,Bimodal Warm - Medium,Thermal Cold	$t(128) = 4.44$	**0.002***
Urgent,Bimodal Warm - Urgent,Thermal Cold	$t(127) = 3.60$	**0.03***
Urgent,Bimodal Warm - Low,Thermal Warm	$t(128) = 6.38$	**<0.0001***
Urgent,Bimodal Warm - Medium,Thermal Warm	$t(128) = 6.66$	**<0.0001***
Urgent,Bimodal Warm - Urgent,Thermal Warm	$t(128) = 2.21$	0.66
Urgent,Bimodal Warm - Low,Vibration	$t(128) = 0.00$	1.00
Urgent,Bimodal Warm - Medium,Vibration	$t(128) = 0.00$	1.00
Urgent,Bimodal Warm - Urgent,Vibration	$t(127) = 0.00$	1.00

Table A.11: Experiment 5: Part 2 of Statistics of *post hoc* tests for the Interaction between Urgency and Modality for Missed Stimuli (*0* Ratings) of the Subjective Rating; significant results are bold and marked with an asterisk.

Urgency,Modality - Urgency,Modality	*t*	*p*
Low,Thermal Cold - Medium,Thermal Cold	*t(170)* = 2.90	0.21
Low,Thermal Cold - Urgent,Thermal Cold	*t(170)* = 4.15	**0.005***
Low,Thermal Cold - Low,Thermal Warm	*t(127)* = 0.00	1.00
Low,Thermal Cold - Medium,Thermal Warm	*t(128)* = 0.28	1.00
Low,Thermal Cold - Urgent,Thermal Warm	*t(128)* = 4.16	**0.005***
Low,Thermal Cold - Low,Vibration	*t(127)* = 6.36	<**0.0001***
Low,Thermal Cold - Medium,Vibration	*t(128)* = 6.38	<**0.0001***
Low,Thermal Cold - Urgent,Vibration	*t(128)* = 6.38	<**0.0001***
Medium,Thermal Cold - Urgent,Thermal Cold	*t(170)* = 1.24	1.00
Medium,Thermal Cold - Low,Thermal Warm	*t(128)* = 1.94	0.83
Medium,Thermal Cold - Medium,Thermal Warm	*t(127)* = 2.21	0.66
Medium,Thermal Cold - Urgent,Thermal Warm	*t(128)* = 2.22	0.65
Medium,Thermal Cold - Low,Vibration	*t(128)* = 4.44	**0.002***
Medium,Thermal Cold - Medium,Vibration	*t(127)* = 4.43	**0.002***
Medium,Thermal Cold - Urgent,Vibration	*t(128)* = 4.44	**0.002***
Urgent,Thermal Cold - Low,Thermal Warm	*t(128)* = 2.78	0.27
Urgent,Thermal Cold - Medium,Thermal Warm	*t(128)* = 3.05	0.15
Urgent,Thermal Cold - Urgent,Thermal Warm	*t(127)* = 1.38	0.99
Urgent,Thermal Cold - Low,Vibration	*t(128)* = 3.61	**0.03***
Urgent,Thermal Cold - Medium,Vibration	*t(128)* = 3.61	**0.03***
Urgent,Thermal Cold - Urgent,Vibration	*t(127)* = 3.60	**0.03***
Low,Thermal Warm - Medium,Thermal Warm	*t(170)* = 0.42	1.00
Low,Thermal Warm - Urgent,Thermal Warm	*t(170)* = 6.22	<**0.0001***
Low,Thermal Warm - Low,Vibration	*t(127)* = 6.36	<**0.0001***
Low,Thermal Warm - Medium,Vibration	*t(128)* = 6.38	<**0.0001***
Low,Thermal Warm - Urgent,Vibration	*t(128)* = 6.38	<**0.0001***
Medium,Thermal Warm - Urgent,Thermal Warm	*t(170)* = 6.64	<**0.0001***
Medium,Thermal Warm - Low,Vibration	*t(128)* = 6.66	<**0.0001***
Medium,Thermal Warm - Medium,Vibration	*t(127)* = 6.64	<**0.0001***
Medium,Thermal Warm - Urgent,Vibration	*t(128)* = 6.66	<**0.0001***
Urgent,Thermal Warm - Low,Vibration	*t(128)* = 2.22	0.65
Urgent,Thermal Warm - Medium,Vibration	*t(128)* = 2.22	0.65
Urgent,Thermal Warm - Urgent,Vibration	*t(127)* = 2.21	0.66
Low,Vibration - Medium,Vibration	*t(170)* = 0.00	1.00
Low,Vibration - Urgent,Vibration	*t(170)* = 0.00	1.00
Medium,Vibration - Urgent,Vibration	*t(170)* = 0.00	1.00

Table A.12: Experiment 5: Part 3 of Statistics of *post hoc* tests for the Interaction between Urgency and Modality for for Missed Stimuli (*0* Ratings) of the Subjective Rating; significant results are bold and marked with an asterisk.

A.6.7 Experiment 5: Statistics of *post hoc* tests for the Interaction between Urgency and Modality for Recognition Rate; significant results and discussion can be found in section 5.2.6

Urgency,Modality - Urgency,Modality	*t*	*p*
Low,Bimodal Cold - Medium,Bimodal Cold	*t(166)* = 0.42	1.00
Low,Bimodal Cold - Urgent,Bimodal Cold	*t(166)* = 1.66	0.94
Low,Bimodal Cold - Low,Bimodal Warm	*t(179)* = 1.12	1.00
Low,Bimodal Cold - Medium,Bimodal Warm	*t(189)* = 0.72	1.00
Low,Bimodal Cold - Urgent,Bimodal Warm	*t(189)* = 2.16	0.69
Low,Bimodal Cold - Low,Thermal Cold	*t(179)* = 2.60	0.38
Low,Bimodal Cold - Medium,Thermal Cold	*t(189)* = 3.60	**0.03***
Low,Bimodal Cold - Urgent,Thermal Cold	*t(189)* = 5.87	**0.0002***
Low,Bimodal Cold - Low,Thermal Warm	*t(179)* = 4.28	**0.003***
Low,Bimodal Cold - Medium,Thermal Warm	*t(189)* = 4.32	**0.002***
Low,Bimodal Cold - Urgent,Thermal Warm	*t(189)* = 4.69	**0.0005***
Low,Bimodal Cold - Low,Vibration	*t(179)* = 1.12	1.00
Low,Bimodal Cold - Medium,Vibration	*t(189)* = 0.72	1.00
Low,Bimodal Cold - Urgent,Vibration	*t(189)* = 0.90	1.00
Medium,Bimodal Cold - Urgent,Bimodal Cold	*t(166)* = 2.08	0.75
Medium,Bimodal Cold - Low,Bimodal Warm	*t(189)* = 0.72	1.00
Medium,Bimodal Cold - Medium,Bimodal Warm	*t(179)* = 0.37	1.00
Medium,Bimodal Cold - Urgent,Bimodal Warm	*t(189)* = 2.52	0.43
Medium,Bimodal Cold - Low,Thermal Cold	*t(189)* = 2.16	0.69
Medium,Bimodal Cold - Medium,Thermal Cold	*t(179)* = 3.35	0.07
Medium,Bimodal Cold - Urgent,Thermal Cold	*t(189)* = 4.50	**0.001***
Medium,Bimodal Cold - Low,Thermal Warm	*t(189)* = 3.78	**0.02***
Medium,Bimodal Cold - Medium,Thermal Warm	*t(179)* = 4.09	**0.006***
Medium,Bimodal Cold - Urgent,Thermal Warm	*t(189)* = 4.32	**0.002***
Medium,Bimodal Cold - Low,Vibration	*t(189)* = 0.72	1.00
Medium,Bimodal Cold - Medium,Vibration	*t(179)* = 0.37	1.00
Medium,Bimodal Cold - Urgent,Vibration	*t(189)* = 1.26	1.00

Table A.13: Experiment 5: Part 1 Statistics of *post hoc* tests for the Interaction between Urgency and Modality for Recognition Rate; significant results are bold and marked with an asterisk.

Urgency,Modality - Urgency,Modality	*t(238)*	*p*
Urgent,Bimodal Cold - Low,Bimodal Warm	*t(189)* = 2.52	0.43
Urgent,Bimodal Cold - Medium,Bimodal Warm	*t(189)* = 2.16	0.69
Urgent,Bimodal Cold - Urgent,Bimodal Warm	*t(179)* = 0.74	1.00
Urgent,Bimodal Cold - Low,Thermal Cold	*t(189)* = 3.96	**0.009***
Urgent,Bimodal Cold - Medium,Thermal Cold	*t(189)* = 5.05	**0.0001***
Urgent,Bimodal Cold - Urgent,Thermal Cold	*t(179)* = 6.51	<**0.0001***
Urgent,Bimodal Cold - Low,Thermal Warm	*t(189)* = 5.59	<**0.0001***
Urgent,Bimodal Cold - Medium,Thermal Warm	*t(189)* = 5.77	<**0.0001***
Urgent,Bimodal Cold - Urgent,Thermal Warm	*t(179)* = 6.32	<**0.0001***
Urgent,Bimodal Cold - Low,Vibration	*t(189)* = 2.52	0.43
Urgent,Bimodal Cold - Medium,Vibration	*t(189)* = 2.16	0.69
Urgent,Bimodal Cold - Urgent,Vibration	*t(179)* = 0.56	1.00
Low,Bimodal Warm - Medium,Bimodal Warm	*t(166)* = 0.42	1.00
Low,Bimodal Warm - Urgent,Bimodal Warm	*t(166)* = 3.74	**0.02***
Low,Bimodal Warm - Low,Thermal Cold	*t(179)* = 1.49	0.98
Low,Bimodal Warm - Medium,Thermal Cold	*t(189)* = 2.52	0.43
Low,Bimodal Warm - Urgent,Thermal Cold	*t(189)* = 3.78	**0.02***
Low,Bimodal Warm - Low,Thermal Warm	*t(179)* = 3.78	0.11
Low,Bimodal Warm - Medium,Thermal Warm	*t(189)* = 3.24	0.09
Low,Bimodal Warm - Urgent,Thermal Warm	*t(189)* = 3.60	**0.03***
Low,Bimodal Warm - Low,Vibration	*t(179)* = 0.00	1.00
Low,Bimodal Warm - Medium,Vibration	*t(189)* = 0.36	1.00
Low,Bimodal Warm - Urgent,Vibration	*t(189)* = 1.98	0.81
Medium,Bimodal Warm - Urgent,Bimodal Warm	*t(166)* = 3.33	0.07
Medium,Bimodal Warm - Low,Thermal Cold	*t(189)* = 1.80	0.90
Medium,Bimodal Warm - Medium,Thermal Cold	*t(179)* = 2.98	0.17
Medium,Bimodal Warm - Urgent,Thermal Cold	*t(189)* = 4.14	**0.005***
Medium,Bimodal Warm - Low,Thermal Warm	*t(189)* = 3.42	0.05
Medium,Bimodal Warm - Medium,Thermal Warm	*t(179)* = 3.72	**0.02***
Medium,Bimodal Warm - Urgent,Thermal Warm	*t(189)* = 3.96	**0.009***
Medium,Bimodal Warm - Low,Vibration	*t(189)* = 0.36	1.00
Medium,Bimodal Warm - Medium,Vibration	*t(179)* = 0.00	1.00
Medium,Bimodal Warm - Urgent,Vibration	*t(189)* = 1.62	0.95
Urgent,Bimodal Warm - Low,Thermal Cold	*t(189)* = 4.69	**0.0005***
Urgent,Bimodal Warm - Medium,Thermal Cold	*t(189)* = 5.77	<**0.0001***
Urgent,Bimodal Warm - Urgent,Thermal Cold	*t(179)* = 7.25	<**0.0001***
Urgent,Bimodal Warm - Low,Thermal Warm	*t(189)* = 6.31	<**0.0001***
Urgent,Bimodal Warm - Medium,Thermal Warm	*t(189)* = 6.49	<**0.0001***
Urgent,Bimodal Warm - Urgent,Thermal Warm	*t(179)* = 7.07	<**0.0001***
Urgent,Bimodal Warm - Low,Vibration	*t(189)* = 3.24	0.09
Urgent,Bimodal Warm - Medium,Vibration	*t(189)* = 2.88	0.21
Urgent,Bimodal Warm - Urgent,Vibration	*t(179)* = 1.30	0.99

Table A.14: Experiment 5: Part 2 of Statistics of *post hoc* tests for the Interaction between Urgency and Modality for Recognition Rate; significant results are bold and marked with an asterisk.

Urgency,Modality - Urgency,Modality	*t(238)*	*p*
Low,Thermal Cold - Medium,Thermal Cold	*t(166)* = 1.25	1.00
Low,Thermal Cold - Urgent,Thermal Cold	*t(166)* = 2.70	0.31
Low,Thermal Cold - Low,Thermal Warm	*t(179)* = 1.67	0.94
Low,Thermal Cold - Medium,Thermal Warm	*t(189)* = 1.80	0.90
Low,Thermal Cold - Urgent,Thermal Warm	*t(189)* = 2.16	0.69
Low,Thermal Cold - Low,Vibration	*t(179)* = 1.49	0.98
Low,Thermal Cold - Medium,Vibration	*t(189)* = 1.80	0.90
Low,Thermal Cold - Urgent,Vibration	*t(189)* = 3.42	0.05
Medium,Thermal Cold - Urgent,Thermal Cold	*t(166)* = 1.46	0.98
Medium,Thermal Cold - Low,Thermal Warm	*t(189)* = 0.54	1.00
Medium,Thermal Cold - Medium,Thermal Warm	*t(179)* = 0.74	1.00
Medium,Thermal Cold - Urgent,Thermal Warm	*t(189)* = 1.08	1.00
Medium,Thermal Cold - Low,Vibration	*t(189)* = 2.52	0.43
Medium,Thermal Cold - Medium,Vibration	*t(179)* = 2.98	0.17
Medium,Thermal Cold - Urgent,Vibration	*t(189)* = 4.50	**0.001***
Urgent,Thermal Cold - Low,Thermal Warm	*t(189)* = 0.72	1.00
Urgent,Thermal Cold - Medium,Thermal Warm	*t(189)* = 0.54	1.00
Urgent,Thermal Cold - Urgent,Thermal Warm	*t(179)* = 0.19	1.00
Urgent,Thermal Cold - Low,Vibration	*t(189)* = 3.78	**0.02***
Urgent,Thermal Cold - Medium,Vibration	*t(189)* = 4.14	**0.005***
Urgent,Thermal Cold - Urgent,Vibration	*t(179)* = 5.95	<**0.0001***
Low,Thermal Warm - Medium,Thermal Warm	*t(166)* = 0.21	1.00
Low,Thermal Warm - Urgent,Thermal Warm	*t(166)* = 0.62	1.00
Low,Thermal Warm - Low,Vibration	*t(179)* = 3.16	0.11
Low,Thermal Warm - Medium,Vibration	*t(189)* = 3.42	0.05
Low,Thermal Warm - Urgent,Vibration	*t(189)* = 5.05	**0.0001***
Medium,Thermal Warm - Urgent,Thermal Warm	*t(166)* = 0.42	1.00
Medium,Thermal Warm - Low,Vibration	*t(189)* = 3.24	0.09
Medium,Thermal Warm - Medium,Vibration	*t(179)* = 3.72	**0.02***
Medium,Thermal Warm - Urgent,Vibration	*t(189)* = 5.23	<**0.0001***
Urgent,Thermal Warm - Low,Vibration	*t(189)* = 3.70	**0.03***
Urgent,Thermal Warm - Medium,Vibration	*t(189)* = 3.96	**0.009***
Urgent,Thermal Warm - Urgent,Vibration	*t(179)* = 5.76	<**0.0001***
Low,Vibration - Medium,Vibration	*t(166)* = 0.42	1.00
Low,Vibration - Urgent,Vibration	*t(166)* = 2.29	0.60
Medium,Vibration - Urgent,Vibration	*t(166)* = 1.87	0.86

Table A.15: Experiment 5: Part 3 of Statistics of *post hoc* tests for the Interaction between Urgency and Modality for Recognition Rate; significant results are bold and marked with an asterisk.

A.6.8 Experiment 5: Statistics of *post hoc* tests for the Interaction between Urgency and Modality for Recognition Time; significant results and discussion can be found in section 5.2.6

Urgency,Modality - Urgency,Modality	*t*	*p*
Low,Bimodal Cold - Medium,Bimodal Cold	$t(152) = 0.44$	1.00
Low,Bimodal Cold - Urgent,Bimodal Cold	$t(153) = 2.89$	0.21
Low,Bimodal Cold - Low,Bimodal Warm	$t(182) = 0.69$	1.00
Low,Bimodal Cold - Medium,Bimodal Warm	$t(196) = 0.55$	1.00
Low,Bimodal Cold - Urgent,Bimodal Warm	$t(196) = 2.13$	0.71
Low,Bimodal Cold - Low,Thermal Cold	$t(183) = 1.85$	0.87
Low,Bimodal Cold - Medium,Thermal Cold	$t(191) = 1.43$	0.98
Low,Bimodal Cold - Urgent,Thermal Cold	$t(192) = 0.16$	1.00
Low,Bimodal Cold - Low,Thermal Warm	$t(182) = 2.56$	0.40
Low,Bimodal Cold - Medium,Thermal Warm	$t(191) = 2.33$	0.57
Low,Bimodal Cold - Urgent,Thermal Warm	$t(191) = 2.19$	0.68
Low,Bimodal Cold - Low,Vibration	$t(182) = 2.41$	0.51
Low,Bimodal Cold - Medium,Vibration	$t(196) = 2.49$	0.46
Low,Bimodal Cold - Urgent,Vibration	$t(196) = 4.35$	**0.002***
Medium,Bimodal Cold - Urgent,Bimodal Cold	$t(153) = 2.47$	0.47
Medium,Bimodal Cold - Low,Bimodal Warm	$t(196) = 0.30$	1.00
Medium,Bimodal Cold - Medium,Bimodal Warm	$t(182) = 0.15$	1.00
Medium,Bimodal Cold - Urgent,Bimodal Warm	$t(195) = 1.74$	0.92
Medium,Bimodal Cold - Low,Thermal Cold	$t(194) = 2.31$	0.59
Medium,Bimodal Cold - Medium,Thermal Cold	$t(181) = 1.77$	0.91
Medium,Bimodal Cold - Urgent,Thermal Cold	$t(193) = 0.56$	1.00
Medium,Bimodal Cold - Low,Thermal Warm	$t(191) = 3.04$	0.15
Medium,Bimodal Cold - Medium,Thermal Warm	$t(182) = 2.63$	0.36
Medium,Bimodal Cold - Urgent,Thermal Warm	$t(190) = 2.58$	0.39
Medium,Bimodal Cold - Low,Vibration	$t(196) = 2.03$	0.78
Medium,Bimodal Cold - Medium,Vibration	$t(182) = 2.06$	0.76
Medium,Bimodal Cold - Urgent,Vibration	$t(195) = 3.96$	**0.009***

Table A.16: Experiment 5: Part 1 Statistics of *post hoc* tests for the Interaction between Urgency and Modality for Recognition Time; significant results are bold and marked with an asterisk.

Urgency,Modality - Urgency,Modality	*t*	*p*
Urgent,Bimodal Cold - Low,Bimodal Warm	*t(195)* = 1.99	0.80
Urgent,Bimodal Cold - Medium,Bimodal Warm	*t(195)* = 2.15	0.70
Urgent,Bimodal Cold - Urgent,Bimodal Warm	*t(182)* = 0.56	1.00
Urgent,Bimodal Cold - Low,Thermal Cold	*t(194)* = 4.51	**0.001***
Urgent,Bimodal Cold - Medium,Thermal Cold	*t(193)* = 4.03	**0.007***
Urgent,Bimodal Cold - Urgent,Thermal Cold	*t(181)* = 2.72	0.30
Urgent,Bimodal Cold - Low,Thermal Warm	*t(192)* = 5.21	**<0.0001***
Urgent,Bimodal Cold - Medium,Thermal Warm	*t(191)* = 4.90	**0.0002***
Urgent,Bimodal Cold - Urgent,Thermal Warm	*t(181)* = 4.66	**0.0006***
Urgent,Bimodal Cold - Low,Vibration	*t(196)* = 0.26	1.00
Urgent,Bimodal Cold - Medium,Vibration	*t(195)* = 0.21	1.00
Urgent,Bimodal Cold - Urgent,Vibration	*t(182)* = 1.64	0.95
Low,Bimodal Warm - Medium,Bimodal Warm	*t(152)* = 0.16	1.00
Low,Bimodal Warm - Urgent,Bimodal Warm	*t(153)* = 1.54	0.97
Low,Bimodal Warm - Low,Thermal Cold	*t(183)* = 2.50	0.44
Low,Bimodal Warm - Medium,Thermal Cold	*t(191)* = 2.11	0.73
Low,Bimodal Warm - Urgent,Thermal Cold	*t(192)* = 0.85	1.00
Low,Bimodal Warm - Low,Thermal Warm	*t(182)* = 3.21	0.10
Low,Bimodal Warm - Medium,Thermal Warm	*t(191)* = 3.00	0.16
Low,Bimodal Warm - Urgent,Thermal Warm	*t(191)* = 2.86	0.23
Low,Bimodal Warm - Low,Vibration	*t(182)* = 1.72	0.93
Low,Bimodal Warm - Medium,Vibration	*t(196)* = 1.79	0.90
Low,Bimodal Warm - Urgent,Vibration	*t(196)* = 3.65	**0.03***
Medium,Bimodal Warm - Urgent,Bimodal Warm	*t(153)* = 1.71	0.93
Medium,Bimodal Warm - Low,Thermal Cold	*t(194)* = 2.45	0.48
Medium,Bimodal Warm - Medium,Thermal Cold	*t(181)* = 1.91	0.84
Medium,Bimodal Warm - Urgent,Thermal Cold	*t(193)* = 0.70	1.00
Medium,Bimodal Warm - Low,Thermal Warm	*t(191)* = 3.18	0.10
Medium,Bimodal Warm - Medium,Thermal Warm	*t(182)* = 2.77	0.27
Medium,Bimodal Warm - Urgent,Thermal Warm	*t(190)* = 2.72	0.30
Medium,Bimodal Warm - Low,Vibration	*t(196)* = 1.88	0.86
Medium,Bimodal Warm - Medium,Vibration	*t(182)* = 1.92	0.84
Medium,Bimodal Warm - Urgent,Vibration	*t(195)* = 3.81	**0.02***
Urgent,Bimodal Warm - Low,Thermal Cold	*t(194)* = 3.97	**0.009***
Urgent,Bimodal Warm - Medium,Thermal Cold	*t(193)* = 3.49	**0.04***
Urgent,Bimodal Warm - Urgent,Thermal Cold	*t(181)* = 2.19	0.67
Urgent,Bimodal Warm - Low,Thermal Warm	*t(192)* = 4.67	**0.0005***
Urgent,Bimodal Warm - Medium,Thermal Warm	*t(191)* = 4.27	**0.002***
Urgent,Bimodal Warm - Urgent,Thermal Warm	*t(181)* = 4.13	**0.005***
Urgent,Bimodal Warm - Low,Vibration	*t(196)* = 0.30	1.00
Urgent,Bimodal Warm - Medium,Vibration	*t(195)* = 0.35	1.00
Urgent,Bimodal Warm - Urgent,Vibration	*t(181)* = 2.20	0.67

Table A.17: Experiment 5: Part 2 of Statistics of *post hoc* tests for the Interaction between Urgency and Modality for Recognition Time; significant results are bold and marked with an asterisk.

Urgency,Modality - Urgency,Modality	*t*	*p*
Low,Thermal Cold - Medium,Thermal Cold	$t(151) = 0.53$	1.00
Low,Thermal Cold - Urgent,Thermal Cold	$t(151) = 1.82$	0.89
Low,Thermal Cold - Low,Thermal Warm	$t(183) = 0.69$	1.00
Low,Thermal Cold - Medium,Thermal Warm	$t(191) = 0.41$	1.00
Low,Thermal Cold - Urgent,Thermal Warm	$t(190) = 0.27$	1.00
Low,Thermal Cold - Low,Vibration	$t(183) = 4.12$	**0.005***
Low,Thermal Cold - Medium,Vibration	$t(194) = 4.32$	**0.002***
Low,Thermal Cold - Urgent,Vibration	$t(194) = 6.11$	<**0.0001***
Medium,Thermal Cold - Urgent,Thermal Cold	$t(152) = 1.35$	0.99
Medium,Thermal Cold - Low,Thermal Warm	$t(188) = 1.22$	1.00
Medium,Thermal Cold - Medium,Thermal Warm	$t(181) = 0.87$	1.00
Medium,Thermal Cold - Urgent,Thermal Warm	$t(188) = 0.77$	1.00
Medium,Thermal Cold - Low,Vibration	$t(191) = 3.80$	**0.02***
Medium,Thermal Cold - Medium,Vibration	$t(181) = 3.75$	**0.02***
Medium,Thermal Cold - Urgent,Vibration	$t(193) = 5.64$	<**0.0001***
Urgent,Thermal Cold - Low,Thermal Warm	$t(189) = 2.42$	0.50
Urgent,Thermal Cold - Medium,Thermal Warm	$t(190) = 2.11$	0.73
Urgent,Thermal Cold - Urgent,Thermal Warm	$t(181) = 1.90$	0.85
Urgent,Thermal Cold - Low,Vibration	$t(192) = 2.53$	0.42
Urgent,Thermal Cold - Medium,Vibration	$t(193) = 2.57$	0.40
Urgent,Thermal Cold - Urgent,Vibration	$t(181) = 4.29$	**0.003***
Low,Thermal Warm - Medium,Thermal Warm	$t(151) = 0.33$	1.00
Low,Thermal Warm - Urgent,Thermal Warm	$t(151) = 0.49$	1.00
Low,Thermal Warm - Low,Vibration	$t(182) = 4.81$	**0.0003***
Low,Thermal Warm - Medium,Vibration	$t(191) = 5.03$	**0.0001***
Low,Thermal Warm - Urgent,Vibration	$t(192) = 6.78$	<**0.0001***
Medium,Thermal Warm - Urgent,Thermal Warm	$t(151) = 0.16$	1.00
Medium,Thermal Warm - Low,Vibration	$t(191) = 4.66$	**0.0006***
Medium,Thermal Warm - Medium,Vibration	$t(182) = 4.56$	**0.0009***
Medium,Thermal Warm - Urgent,Vibration	$t(191) = 6.49$	<**0.0001***
Urgent,Thermal Warm - Low,Vibration	$t(191) = 4.52$	**0.001***
Urgent,Thermal Warm - Medium,Vibration	$t(190) = 4.58$	**0.0008***
Urgent,Thermal Warm - Urgent,Vibration	$t(181) = 6.20$	<**0.0001***
Low,Vibration - Medium,Vibration	$t(152) = 0.06$	1.00
Low,Vibration - Urgent,Vibration	$t(153) = 2.06$	0.76
Medium,Vibration - Urgent,Vibration	$t(153) = 2.01$	0.79

Table A.18: Experiment 5: Part 3 of Statistics of *post hoc* tests for the Interaction between Urgency and Modality for Recognition Time; significant results are bold and marked with an asterisk.

A.7 Experiment 6

A.7.1 Experiment 6: Information Sheet

BiModalInfo – Investigating Thermal and Vibrotactile Feedback on the Steering Wheel

BACKGROUND

The goal of this user study is to improve safety in driving situations by providing notifications with different levels of information through thermal feedback with and without vibration on the steering wheel.

TASK

The study will be conducted in a driving simulator and you will be asked to identify notifications consisting of thermal (unimodal) or thermal and vibrotactile (bimodal) feedback. You will perform the tasks sitting in a gaming racing chair. There will be a steering wheel securely attached in front of you and you will be holding the wheel throughout the experiment. Please position your hands on the indicated location of the steering wheel and keep them on the devices. You will be wearing headphones throughout the experiment, playing car sounds.

In the simulated driving you will perform a lane change task while the stimuli are being presented. The simulator requires you to keep a virtual vehicle within the limits of the road. The car will be placed on a five-lane motorway. You will start in the middle lane and should swiftly and precisely change to another lane, when it is indicated by an arrow on one of the bridges and reach the goal lane before reaching that bridge. Please keep then within that lane, until another arrow appears. In between these lane changes you might be presented with notifications, which you should identify as swiftly as possible by reporting the importance (high/low) and the nature (work/private) of the received message to the experimenter.

There will be a training phase before the main driving task begins. The driving task itself will be separated into five blocks of approximately 5 min each. You can break between these blocks, but please let the experimenter know, if you need to rest within a block.

INSTRUCTIONS

- Please place both hands at the indicated spaces on the steering wheel while driving.
- In the driving task, please try to follow the instructions given by the arrows on the bridges to the best of your ability and try to keep inside the lane.

MISCELLANEOUS

- You will be wearing headphones throughout the experiment.
- The experiment is divided into blocks. You can rest between the blocks for as long as you need. If additional breaks are required, please let the experimenter know.
- You can withdraw from the study at any time without penalty. The data recorded until then will be destroyed.

IMPORTANT

The systems you interact with will not ask or store personal information and all data recorded are anonymised. The study will take approximately 60 minutes to complete and a 10£ Amazon voucher will be handed out at the end. If you are a student, no course credits will be awarded for completing this study. To take part in this study, the following criteria must be met:

- I am at least 18 years old
- I hold a full driving licence
- I have no visual impairments (not including wearing glasses or contact lenses)
- I have no neurological disorders (e.g. epilepsy)
- I do not suffer from motion sickness
- I do not have any sensory impairments

You will be given resting sessions between experimental conditions but please do not be afraid to ask for a break if required at any time during the study. Furthermore, if you feel unwell at any point, please let the experimenter know immediately so that medical attention can be given as soon as possible. Should you have any questions about the study or like more information about our research in general, contact details are provided below.

CONTACT DETAILS

Name:	Patrizia Di Campli San Vito (PhD student/Experimenter)
Email:	p.di-campli-san-vito.1@research.gla.ac.uk
Office:	Room F141, Sir Alwyn Williams Building (Computing Science), Glasgow, G12 8RZ, Scotland
Supervisor:	Professor Stephen Brewster
Email:	stephen.brewster@glasgow.ac.uk
Office:	Room S131, Sir Alwyn Williams Building (Computing Science), Glasgow, G12 8RZ, Scotland
Tel:	+44 (0)141-330-4966

This study has been approved by the Ethics Committee (Reference Number - 300160073).

This research is part funded by the EPSRC and Jaguar Land Rover.

A.7.2 Experiment 6: Consent Form

BiModalInfo – Investigating Thermal and Vibrotactile Feedback on the Steering Wheel

CONSENT FORM

☐ I confirm that I have read and understood the Study Information Sheet provided to me for the above study and have had the opportunity to ask questions.

☐ The study has been explained to me, and I understand the explanation given and what my participation will involve.

☐ I understand that during the course of the study the experimenter will give additional instructions concerning the experiment and that the purpose of some of the instructions will only be explained at the end of the study.

☐ I understand that my participation is voluntary and that I am free to withdraw at any time, without giving a reason.

☐ I understand that the research data may be accessed by researchers working at the GIST, but that at all times my personal data will be kept confidential in accordance with data protection guidelines.

I have initialled the above boxes myself and I agree to take part in the study.

FULL NAME: ____

SIGNATURE: ____

DATE: ____

I want to be added to the participant's pool: ☐ YES ☐ NO

EMAIL: ____

Experimenter: Ms Patrizia Di Campli San Vito
(p.di-campli-san-vito.1@research.gla.ac.uk)

DATE, SIGNATURE: ____

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 - 300160073).

This research is part funded by the EPSRC and Jaguar Land Rover.

JAGUAR | LAND ROVER | University of Glasgow | School of Computing Science | GIST Glasgow Interactive Systems Group

A.7.3 Experiment 6: Questionnaires

BiModalInfo

1
Responses

00:59
Average time to complete

Active
Status

1. Participant ID

1
Responses

Latest responses
"P00"

2. Age

1
Responses

Latest responses
"0"

3. Gender

Male	0
Female	0
Non-Binary	0
Prefer not to say	1

4. Occupation

1
Responses

Latest responses
"-"

5. Years of driving experience

1
Responses

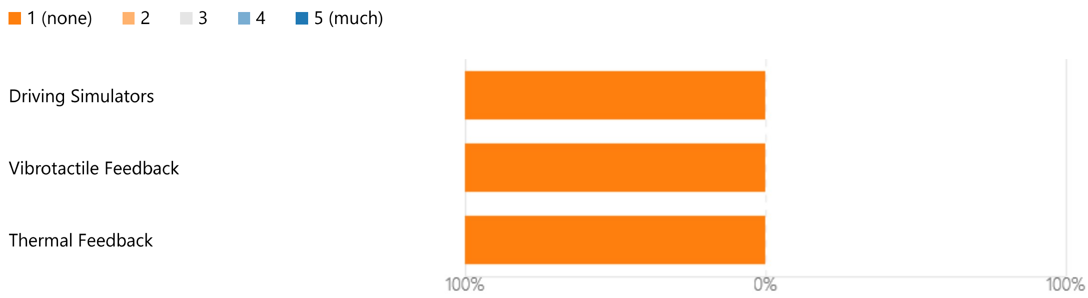
Latest responses
"0"

6. Country in which the driving license was obtained

1
Responses

Latest responses
"-"

7. Please report on how much experience with the technologies you had prior to the experiment:



8. How much did you like the unimodal (only thermal) notifications?

1
Responses

1.00 Average Rating

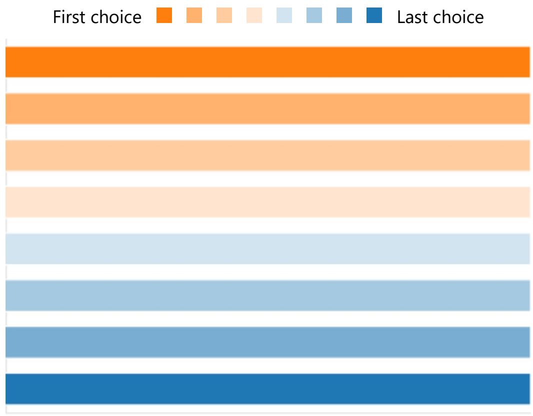
9. How much did you like the bimodal (thermal and vibrotactile) notifications?

1
Responses

1.00 Average Rating

10. Please rank the different stimuli on how well you could identify them:

Rank	Options
1	High Importance Private Ther...
2	High Importance Work Thermal
3	Low Importance Private Ther...
4	Low Importance Work Thermal
5	High Importance Private Bimo...
6	High Importance Work Bimodal
7	Low Importance Private Bimo...
8	Low Importance Work Bimodal



11. Please name reasons for your rating:

1
Responses

Latest responses
"-"

12. How well could you differentiate the direction of temperature change (private/work)?

1
Responses

★☆☆☆☆
1.00 Average Rating

13. How well could you differentiate the vibration patterns (importance in bimodal stimuli)?

1
Responses

★☆☆☆☆
1.00 Average Rating

14. How well could you differentiate the lengths of temperature presentation (importance in thermal stimuli)?

1
Responses

★☆☆☆☆
1.00 Average Rating

15. Comments:

0
Responses

Latest responses

A.8 Experiment 7

A.8.1 Experiment 7: Information Sheet

Investigating Feedback for Handover Scenarios

INFORMATION SHEET

This study investigates different feedback types for handover scenarios in semiautonomous cars. In a handover scenario the driver transfers the control to the car, i.e. switches from manual to autonomous driving. In this study the driver should activate the traffic jam pilot when it is available, allowing the car to manoeuvre through a traffic jam by itself. This study is conducted in a driving simulator.

Overall you will be asked to activate the pilot four different times, in four different driving blocks. You should activate the traffic jam pilot as soon as it is available. This can be achieved by pressing two buttons on the steering wheel or the paddle shifters for three seconds. Different feedback will support the handover process and may include audio, visual and haptic cues. The specific type of handover and feedback will be explained to you before each block.

The simulator requires you to keep a virtual vehicle within the limits of the road, just like in real life. You will interact with the haptic steering wheel to control the virtual driving task. You will have time to get used to the simulator. You will be asked to fill in questionnaires between the blocks. There will be short breaks between the blocks, but if you need to have a break at any other time, please notify the experimenter.

You should be aware that there is some risk of induced motion sickness when using a driving simulator - if you are particularly susceptible to motion sickness, migraines, epilepsy, dizziness or blurred vision then you should not take part. We advise that you wait for 30 minutes before driving your own car after the end of the study.

INSTRUCTIONS

- Please drive as you would drive in a real car.
- Please try to follow the instructions given by the system to the best of your ability and try to keep inside the lane.

MISCELLANEOUS

- There will be video recordings of your face, your hands and your feet. These recordings will be used for analysis purposes only and will not be shared. You can request at any point for this data to be deleted.
- You can end the experiment at any time without any judgement. The data recorded until then will be destroyed.

IMPORTANT

The systems you interact with will not ask or store personal information and all data recorded is anonymised. You will be filmed during the experiment, but the footage is for internal use only and will not be published directly at any point, however anonymized summaries of driving behaviour might be used for academic publications. Images will not be used without your permission. The study will take approximately 60 minutes to complete. You can withdraw from the study at any time without penalty.

Investigating Feedback for Handover Scenarios

<u>To take part in this study, the following criteria must be met:</u>

- I am at least 18 years old
- I hold a full driving licence
- I have no visual impairments (not including wearing glasses or contact lenses)
- I have no neurological disorders (e.g. epilepsy)
- I do not suffer from motion sickness
- I do not have any sensory impairments

You will be given resting sessions between experimental conditions but please do not be afraid to ask for a break, if required, at any time during the study. Furthermore, if you feel unwell at any point, please let the experimenter know immediately so that medical attention can be given as soon as possible. You can withdraw from the study at any time without prejudice and all data recorded to that point will be erased. If you have any questions about the study or would like more information about our research in general, contact details are provided below.

CONTACT DETAILS

Name: Patrizia Di Campli San Vito (PhD student/Experimenter)

Email: p.di-campli-san-vito.1@research.gla.ac.uk, pdicampl@partner.jaguarlandrover.com

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ebrown6@jaguarlandrover.com

Supervisor UofG: Professor Stephen Brewster

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This research is funded by Jaguar Land Rover and EPSRC and has been approved by the Ethics Committee of JLR (number:) and the University of Glasgow (number:).

Version No. 1 (November 2018)

A.8.2 Experiment 7: Consent Form

Investigating Feedback for Handover Scenarios

CONSENT FORM

☐ I confirm that I have read and understood the Study Information Sheet provided to me for the above study and have had the opportunity to ask questions.

☐ The study has been explained to me, and I understand the explanation given and what my participation will involve.

☐ I understand that during the study the experimenter will give additional instructions concerning the experiment and that the purpose of some of the instructions will only be explained at the end of the study.

☐ I understand that my participation is voluntary and that I am free to withdraw at any time, without giving a reason.

☐ I understand that the research data may be accessed by researchers working at the Jaguar Land Rover and the Glasgow Interaction Section, but that at all times my personal data will be kept confidential in accordance with data protection guidelines.

☐ I understand and agree that during the study video footage will be recorded for analysis purposes.

☐ I understand and consent that parts of the video data may be presented to JLR staff for demonstration purposes.

☐ I understand that I can ask for my data to be deleted at any time.

I have initialled the above boxes myself and I agree to take part in the study.

FULL NAME: ____

SIGNATURE: ____

DATE: ____

EMAIL: ____

Experimenter: Patrizia Di Campli San Vito
(p.di-campli-san-vito.1@research.gla.ac.uk, pdicampl@partner.jaguarlandrover.com)

DATE, SIGNATURE: ____

Supervisor details: Eddie Brown
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Professor Stephen Brewster
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This research is funded by Jaguar Land Rover and EPSRC and has been approved by the Ethics Committees of JLR and the University of Glasgow.

A.8.3 Experiment 7: Questionnaires

Condition Rating

Please rate your experience with the Transfer Control Condition you just experienced

* Required

1. **Participant** *

2. **Condition** *
Mark only one oval.
   - Buttons
   - Paddles with Audio and Visual (NoHapVis)
   - Paddles with Audio, Visual and Haptics (HapVis)
   - Paddles with Audio and Haptics (HapNoVis)

3. **Mental Demand** *
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Low											High

4. **Physical Demand** *
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Low											High

5. **Time Pressure** *
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Low											High

6. **Effort** *
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Low											High

7. **Performance** *
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Poor											Good

8. **Frustration** *
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Low											High

9. **Annoyance** *
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Low											High

10. **Complicated** *
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not At All											Very Much

11. **Pleasant** *
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not At All											Very Much

12. **Disruptive** *
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not At All											Very Much

13. **Comfortable** *
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not At All											Very Much

14. **When you transferred from manual driving to autonomous driving, when did the car take over control? ***

15. **When you transferred from autonomous driving to manual driving, when did you take over control? ***

16. **Comments**

Powered by
Google Forms

Questionnaire End

* Required

1. **Participant** *

2. **Please order the conditions from most favourite (1) to least favourite (4)** *
Mark only one oval per row.

	1 (favourite)	2	3	4 (least favourite)
Buttons				
Paddles with Audio and Visual (NoHapVis)				
Paddles with Audio, Visual and Haptics (HapVis)				
Paddles with Audio and Haptics (HapNoVis)				

3. **How well could you feel the thermal feedback during the transfer of control?**
Mark only one oval per row.

	1 (not at all)	2	3	4	5 (very much)
With visual progress bar					
Without visual progress bar					

4. **Did the type of handover influence your trust in the system?** *
Mark only one oval.

- Yes
- No
- Maybe
- Other:

Please rate your trust in the system during the different transfer conditions:

5. **Buttons** *
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Very Trustworthy											Not Trustworthy

6. **Paddles with Audio and Visual (NoHapVis)** *
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Very Trustworthy	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Not Trustworthy

7. **Paddles with Audio, Visual and Haptics (HapVis)** *
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Very Trustworthy	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Not Trustworthy

8. **Paddles with Audio and Haptics (HapNoVis)** *
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Very Trustworthy	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Not Trustworthy

Demographic Data

9. **Age** *

10. **Gender** *
Mark only one oval.

- ◯ Female
- ◯ Male
- ◯ Non-binary
- ◯ Prefer not to say

11. **Which hand is your dominant hand?** *
Mark only one oval.

- ◯ Left
- ◯ Right
- ◯ Both

12. **What is your occupation?** *

13. **How many years of driving experience do you have?** *

14. **Please rate how familiar you where with the following prior to the experiment:** *
Mark only one oval per row.

	1 (Not familiar at all)	2	3	4	5 (very familiar)
Semi-autonomous Features	◯	◯	◯	◯	◯
Driving Simulator	◯	◯	◯	◯	◯
Thermal Feedback	◯	◯	◯	◯	◯
Vibrotactile Feedback	◯	◯	◯	◯	◯

15. **Comments**

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