MULTIMODAL FEEDBACK FOR MID-AIR GESTURES WHEN DRIVING

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SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF
Doctor of Philosophy

SCHOOL OF COMPUTING SCIENCE

COLLEGE OF SCIENCE AND ENGINEERING
UNIVERSITY OF GLASGOW

NOVEMBER 2019

Abstract

Mid-air gestures in cars are being used by an increasing number of drivers on the road. Usability concerns mean good feedback is important, but a balance needs to be found between supporting interaction and reducing distraction in an already demanding environment. Visual feedback is most commonly used, but takes visual attention away from driving. This thesis investigates novel non-visual alternatives to support the driver during mid-air gesture interaction: Cutaneous Push, Peripheral Lights, and Ultrasound feedback. These modalities lack the expressive capabilities of high resolution screens, but are intended to allow drivers to focus on the driving task. A new form of haptic feedback — Cutaneous Push — was defined. Six solenoids were embedded along the rim of the steering wheel, creating three bumps under each palm. Studies 1, 2, and 3 investigated the efficacy of novel *static* and *dynamic* Cutaneous Push patterns, and their impact on driving performance. In simulated driving studies, the cutaneous patterns were tested. The results showed pattern identification rates of up to 81.3% for *static* patterns and 73.5% for dynamic patterns and 100% recognition of directional cues. Cutaneous Push notifications did not impact driving behaviour nor workload and showed very high user acceptance. Cutaneous Push patterns have the potential to make driving safer by providing non-visual and instantaneous messages, for example to indicate an approaching cyclist or obstacle.

Studies 4 & 5 looked at novel uni- and bimodal feedback combinations of Visual, Auditory, Cutaneous Push, and Peripheral Lights for mid-air gestures and found that non-visual feedback modalities, especially when combined bimodally, offered just as much support for interaction without negatively affecting driving performance, visual attention and cognitive demand. These results provide compelling support for using non-visual feedback from in-car systems, supporting input whilst letting drivers focus on driving.

Studies 6 & 7 investigated the above bimodal combinations as well as uni- and bimodal Ultrasound feedback during the Lane Change Task to assess the impact of gesturing and feedback modality on car control during more challenging driving. The results of study Seven suggests that Visual and Ultrasound feedback are not appropriate for in-car usage, unless combined multimodally. If Ultrasound is used uni-modally it is more useful in a binary scenario.

Findings from Studies 5, 6, and 7 suggest that multimodal feedback significantly reduces eyes-off-the-road time compared to Visual feedback without compromising driving performance or perceived user workload, thus it can potentially reduce crash risks. Novel design recommendations for providing feedback during mid-air gesture interaction in cars are provided, informed by the experiment findings.

Acknowledgements

I would like to thank my examiners Andreas Riener and Mary-Ellen Foster.

I am very grateful to a number of people, who have been very instrumental to getting this thesis to completion. Some, however, deserve special mention:

My supervisors — Stephen Brewster and John Williamson who have given unfailing support

To nänä and dädä — who are my biggest fans

To Kemal and Ouassima — because they taught me how to be strong and kind

To Thomas — because he so much like me and yet he is the opposite of me

To each member of MIG — for helping me with all my questions and making my days fun

To each person in SoCS — for supporting me and my cooking competitions

To Frances — simply because she is Frances

To Paddy — because she taught me to appreciate the colour grey

To Phil — for an unexpected friendship with a landlord

To David — for all the hours in level 2 (and that random table tennis tournament that went on and on for hours and hours)

This thesis is dedicated to all the people I love.

Declaration and Contributing Publications

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 attributed to the author:

Study 1 in Chapter 3 has been published in CHI 2016 Late Breaking Work:

> G. Shakeri, A. Ng, J. Williamson, and S. A. Brewster, "Evaluating Haptic Feedback on a Steering Wheel in a Simulated Driving Scenario", in CHI EA 2016.

Study 2 in Chapter 3 has been published in Automotive UI 2016:

> G. Shakeri, A. Ng, J. Williamson, and S. Brewster, "Evaluation of haptic patterns on a steering wheel", in AutoUI 2016.

Study 3 in Chapter 3 will be submitted to AutoUI 2020:

> G. Shakeri, J. Williamson, and S. A. Brewster, "Dynamic Cutaneous Push Feedback from the Steering Wheel", submitted to CHI 2020.

Study 4 in Chapter 4 has been published in Automotive UI 2017:

> G. Shakeri, J. Williamson, and S. Brewster, "Novel Multimodal Feedback Techniques for In-Car Mid-Air Gesture Interaction", in AutoUI 2017.

Studies 5 and 6 in Chapter 5 have been published in ICMI 2017 Demos:

> G. Shakeri, J. Williamson, and S. Brewster, "Bimodal Feedback for In-Car Mid-Air Gesture Interaction", in ICMI Demos 2017.

Study 7 in Chapter 5 has been published in Automotive UI 2018:

G. Shakeri, J. H. Williamson, and S. Brewster, "May the Force Be with You: Ultrasound Haptic Feedback for Mid-Air Gesture Interaction in Cars", in AutoUI 2018.

Summary of this research has been published in a Doctoral Consortium in SICSA HCI 2016:

G. Shakeri, "Novel Multimodal Mid-Air Gesture Displays for Drivers", SICSA HCI Doctoral Consortium 2016.

Ideas developed in this thesis contributed to a DIS 2017 workshop on Autonomous Driving, namely "Setting the Stage with Metaphors for Interaction":

A. Loriette, G. Shakeri, "Agent Metaphor for Autonomous Driving", in DIS 2017 Workshop on Setting the Stage with Metaphors for Interaction.

Finally, ideas developed in this thesis contributed to a demo in CHI 2019:

G. Shakeri, E. Freeman, C. Andersson, W. Frier, M. Iodice, B. Long, O. Georgiou, "Three-in-one: Levitation, ParametricAudio, and Mid-Air Haptic Feedback", CHI Demos 2019.

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Chapter 1

Introduction

1.1 Motivation

Driving is a complex activity which requires high mental and visual attention to be performed successfully. Non-driving related tasks can increase mental workload or distract the driver [22, 23], potentially reducing safety. In 2006, driver distraction was the third most common cause of car crashes and near crash events [24], following driver impairments and driver errors. In 2016, driver distraction was the leading cause of accidents [25]. Introduction of smart infotainment systems and hand-held devices into the car cockpit increased the number and duration of glances off the road [25] significantly affecting all aspects of situational awareness [26]. In order to reduce driver distraction and keep the driver's eyes on the road, many car manufacturers such as VW [27], BMW [28], Jaguar [29], and Hyundai [30] are introducing in-air gestures as a new interaction modality. These gestures allow drivers to control in-car systems without taking their eyes off the road. This has the potential to minimise distraction [31] and improve safety [26] by replacing complex actions (e.g., precisely selecting buttons on touchscreens) with simple hand movements (e.g., swiping the hand in mid-air). A mid-air gesture is a defined movement in space which is used to control a computing system. Gesture control systems are used for a variety of non-driving related tasks such as swiping to browse songs[1] in a playlist, pointing at the screen to accept a phone call[2], or a rotating gesture to change the volume or temperature[2]. This thesis focuses on mid-air gestures, rather than other gesture types; when the term 'gesture' is used, it refers to mid-air gestures.

Due to their novelty, gestures are unfamiliar to most drivers, which may negatively impact driving performance and mental workload [32, 33]. Gestures are also prone to usability challenges which may increase frustration and workload. Users need to know where to perform gestures [34]; drivers may not know where the gesture sensor is located nor in what region it can detect movement. This may mean that they gesture in the wrong place. They

Figure 1.1: Continental's gesture interface [1]. The driver is swiping their hand from left to right to execute a system command.

also need to know how to perform gestures, what the gesture vocabulary is, and how hand movements are mapped to actions. Users may experience uncertainty while gesturing and lack of feedback is a core part of this [35, 36, 37], which can lead to drivers taking their eyes off the road [38], reducing the benefits of the gesture interaction. However, good feedback can overcome these issues. Feedback informs the user whether the system pays attention to them [34], whether the user addressed the system correctly, and whether the user's intention was correctly understood by the system. Feedback further couples the user's hand to the interface [39] and thus mitigates the perceived lack of sense of control from the touch-less interface [35]. Users need good feedback when gesturing in air to avoid increased mental efforts and provide greater user satisfaction [40].

Gesture sensing systems are becoming more omnipresent and it is not always possible to provide feedback on a screen. For instance, recent advances in technology allow for mid-air gesture interaction to be incorporated into limited display devices such as smart watches, thermostats and faucets, and car cockpits. However, in situations, where visual feedback (i.e. standard console screen) might be impractical (e.g. driving), it becomes more important to present feedback to non-visual sensory channels.

Current mid-air gesture systems in cars only give limited (and mainly visual) feedback [28, 27]. If drivers need to take their eyes off the road to understand their interactions with the car, then the benefits of mid-air gestures are not being fully realised. Non-visual feedback is promising for in-car gestures; visual attention can remain on the road whilst information about secondary tasks (i.e. interacting with the in-car systems) is offloaded to other sensory modalities (e.g. hearing and touch) [41]. Throughout this thesis, the term "visual feedback" refers to standard centre console screen feedback as it requires foveal vision for information acquisition. "Non-visual feedback" refers to feedback techniques which present information to the auditory and tactile sensory channels; however, "non-visual" feedback also includes information presentation to the peripheral vision because it does not require the driver's foveal attention i.e. it does not require them to take their eyes off the road.

Multimodal displays have been used successfully in a variety of driving studies to support in-car interaction successfully [42, 43, 44, 45, 14, 46, 47, 48]. The term 'multimodal' feedback refers to delivering information to several sensory channels at the same time [41]. 'Unimodal' displays information to a single sensory channel (e.g. auditory), and 'bimodal' presents information to two sensory channels (e.g. auditory and visual), etc.

Multimodal distribution of infotainment information has been shown to neither increase mental workload [41, 42] nor increase reaction time to cues [42] when executing a challenging driving task, and multimodal displays are preferred by most users over unimodal visual feedback [42, 45, 14, 46, 47, 48]. Multimodal displays deliver information efficiently without negatively impacting driving performance and thus have resulted in many applications in cars. These range from warnings about urgency and situation [49], take-over requests from highly automated cars [9], navigational cues [8, 11, 15], to driving related event information [17].

Multimodal feedback has also been shown to positively impact mid-air gesture interaction [34, 36, 50]. It helps the users to make sense of sensing systems [51, 52] by informing them if the system is paying attention to them, and if the user's command is understood and executed correctly. It has been shown that users regain a sense of control over the interaction [39] if they perceive feedback [35]. Feedback keeps the users "in the loop" and helps them to gesture more effectively and confidently [36].

Evidence discussed so far suggests, that multimodal feedback is beneficial for *non-driving related tasks* and that it is beneficial for *gesture interaction*. Therefore, this thesis presents the design and evaluation of multimodal mid-air gesture feedback for driving scenarios. Three novel feedback types for mid-air gestures are investigated to address and minimise visual distraction, mental workload, and user uncertainty without negatively affecting driving or gesture performance:

- Cutaneous Push (pins on the steering wheel that push against the driver's hand),
- Peripheral Visual displays (using an LED display across the dash board), and
- Ultrasound haptics (ultrasound presented above the gear stick to provide tactile feedback).

These feedback modalities were tested uni- and bimodally, compared to and combined with standard screen displays (using the screen on the centre stack of the car) and audio feedback. The three novel alternatives presented here lack the expressive capabilities of high resolution visual displays, but are intended to allow drivers to focus on what is happening around them. This is of particular importance if the driving task is more challenging and mentally demanding, for example executing driving manoeuvres versus driving straight on a motorway. The experiments conducted showed that these feedback modalities offered strong support for interaction without negatively affecting driving performance, visual attention or cognitive demand. These results provide compelling support for using non-screen feedback for in-car mid-air gestures, supporting input whilst letting drivers focus on driving.

1.2 Thesis Statement

This thesis argues that multimodal feedback can support mid-air gesture interaction in cars and reduce eyes-off-the-road time without affecting driving performance, in a simulated driving task. Tactile, auditory, and peripheral visual displays provide gesture systems a variety of ways of presenting information to in-car mid-air gestures, overcoming the need for visual feedback on screens. This thesis presents the design and evaluation of novel feedback techniques which use these modalities to minimise visual information overload without negatively impacting driving performance.

1.3 Contributions

This thesis makes novel contributions in four areas. First, it contributes a novel tactile feedback technique embedded into a steering wheel. Cutaneous Push feedback is a technology where six solenoids are embedded into the steering wheel under the driver's palms. They are individually controlled to allow patterns and motion presentation to the hands. Two studies focused on recognition rate of different types of patterns, and one study investigated the recognition rate of motion on the palms.

Second, this thesis contributes a study into unimodal feedback for mid-air gestures using three novel feedback types: 1) Peripheral Light displays; 2) Cutaneous Push; and 3) Ultrasound tactile feedback. Peripheral Light displays and ultrasound tactile feedback have been researched in other application areas for in-car infotainment usage [53], however the work presented here is the first detailed study on their use as gesture feedback for in-car interaction. Auditory and Cutaneous Push feedback from the steering wheel allowed drivers to keep their eyes on the road, although feedback given in a single modality was limited, thus increased mental demand of Cutaneous Push compared to standard screen feedback.

Multimodal information displays can be beneficial as information is distributed across multiple sensory modalities. By offloading interaction feedback to other modalities, the demands of interacting with the in-car systems can be reduced. Therefore, this thesis' third contribution is a detailed investigation of the effects of multimodal feedback on mid-air gestures. Two studies looked into the impact of novel bimodal feedback combinations which composed of the output modalities presented above (Peripheral Lights, Cutaneous Push, Ultrasound), and Auditory and Screen (as baseline). The benefit to be gained from this study is reduced mental demand.

Finally, earlier results were extended by examining the effects of the multimodal feedback combinations in more challenging simulated driving situations. In these two studies, drivers executed lane change manoeuvres on a five lane motorway, rather than on a straight road. The studies found that the bimodal feedback techniques presented in this thesis did not negatively affect driving performance, visual attention and cognitive demand.

1.4 Research Questions

This thesis aims to answer the following research questions (all studies were conducted in a simulated driving environment):

- **RQ1:** How effective is Cutaneous Push feedback from the steering wheel to the driver's palm (*Studies 1, 2, & 3*)?
- **RQ2:** How do *unimodal* mid-air gesture feedback techniques influence driving performance and in-car interaction (*Study 4*)?
- **RQ3:** How do *multimodal* mid-air gesture feedback techniques influence driving performance and in-car interaction (*Study 5, 6, & 7*)?
- **RQ4:** What effect does multimodal mid-air gesture feedback have on interaction in more *challenging driving* (*Study 6 & 7*)?

1.5 Thesis Structure

Chapter 2: Literature Review introduces ways to measure driver distraction and driving performance. In-car infotainment systems can distract the driver, which might result in a decrease of the driver's ability to control the car, ultimately impacting the driver's safety. Mid-air gesture interaction can reduce driver distraction if it is accompanied by good feedback to help the user interact. This chapter reviews mid-air gesture feedback techniques in cars addressing usability problems of sensing systems. Finally, it discusses three output modalities — auditory, tactile, and peripheral lights — which can help users gesture more effectively.

Chapter 3: Cutaneous Push Feedback presents an investigation into the efficacy of novel Cutaneous Push feedback patterns, and their impact on driving performance, addressing **RQ1**. Six solenoids were embedded along the edge of the steering wheel, creating three bumps under each palm. In three simulated driving studies, 57 *static* and twenty *dynamic* cutaneous patterns were tested. Later chapters build on this by using a mixture of *static* and *dynamic* Cutaneous Push feedback patterns to aid mid-air gesture interaction in cars.

Chapter 4: Unimodal Feedback for Mid-air Gestures in Cars compares non-visual feedback techniques presented unimodally to standard centre console displays, concerning **RQ2**. This chapter describes a study which measures the impact of Cutaneous Push, peripheral lights, and auditory feedback for mid-air gestures on driving performance and driver distraction.

Chapter 5: Multimodal Feedback for Mid-air Gestures in Cars presents three studies which investigate multimodal feedback, building on the findings of the previous chapter. In the third study, ultrasound feedback is introduced as a novel mid-air gesture modality for cars. These studies contribute an answer to **RQ3**. The latter two studies also incorporate changing lanes on the motorway as opposed to driving straight — i.e. more challenging driving — addressing **RQ4**.

Chapter 6: Conclusion summarises the research conducted in this thesis, and reflects on the research questions identified in the Introduction. It discusses the main contributions of this work, and finally outlines limitations and reviews possibilities for future work.

1.6 Overview of Studies

Seven experimental studies are presented in this thesis, contributing to the research questions outlined in Section 1.4. Three of these focus on the usability of Cutaneous Push as a feedback technique on the steering wheel, one on unimodal, and three on multimodal feedback for mid-air gestures. Table 1.1 shows a brief summary of how each experiment contributed to the research questions.

Topic	Study	Research Questions	Context and Purpose
Cutaneous Push	1	RQ1	Investigate the efficacy of *static* Cutaneous Push feedback from the steering wheel
	2		Investigation of the efficacy of *static* Cutaneous Push feedback from a refined steering wheel
	3		Investigate *dynamic* Cutaneous Push feedback from a steering wheel
Unimodal Feedback for Mid-air Gestures in Cars	4	RQ2	Compare novel feedback modalities for mid-air gestures in cars
	7	RQ2	Investigate efficacy of ultrasound feedback for mid-air gestures in cars
Multimodal Feedback for Mid-air Gestures in Cars	5 6 7	RQ3	Compare novel bimodal feedback for mid-air gestures in cars
Challenging Driving	6 7	RQ4	Compare novel bimodal feedback for mid-air gestures during *more challenging* driving

Table 1.1: Summary of experiments presented in this thesis and research question the studies contributed to answering.

Chapter 2

Literature Review

2.1 Introduction

An increasing number of cars now allow drivers to interact with the in-vehicle systems using mid-air gestures. Whilst intended to reduce driver distraction by replacing visually-demanding button interfaces with 'simple' hand movements, mid-air gestures are not straightforward and usability issues could make them just as distracting. The literature review introduces the challenges of midair gesturing, and discusses multimodal feedback as a way of reducing the usability problems. The use of auditory, tactile, peripheral lights, and multimodal displays have been shown to reduce uncertainty while gesturing [35, 36, 37] and driver's visual distraction [38].

The initial topic of this literature review (Section 2.2) looks at ways of measuring driver distraction and driving performance in research studies. This section does not address any of the research questions, however it introduces the motivation for this work, namely driver distraction. It is necessary to understand 1) driver distraction and 2) driving performance and know how to measure them, if the aim is to reduce the first and maintain the second.

The second topic of this thesis (Section 2.3) discusses whether mid-air gesture interaction is a valuable addition in cars, potentially replacing traditional interfaces like buttons, knobs, touchscreens etc.. This section does not address any of the research questions, but it is imperative to discuss the usefulness of gesture interaction in cars, before discussing the necessity of feedback.

The third topic (Section 2.4) investigates usability issues of mid-air gesture interaction and proposed solutions. Mid-air gestures have found applications and wide usage in gaming, smart-homes, smart phone interaction, and driving environments. Bellotti *et al.* [52] identified usability problems of sensing systems taking inspiration from human-human communication to inform five design challenges of gesture detection systems. These five concerns are: *Address*, *Attention*, *Action*, *Alignment*, and *Accident*. Freeman [51] was the first to explicitly link these concerns to mid-air gestures. He reviewed feedback techniques for limited display devices, addressing each of the five usability concerns identified by Bellotti *et al.*, primarily focusing on the *Address* problem. The second topic of this thesis (Section 2.4) builds on Bellotti *et al.*'s and Freeman's work. It discusses available literature on mid-air gesture feedback for in-car interaction by addressing each of the five usability problems, with the focus on *Address*, *Attention*, and *Alignment*. Since there is very limited literature on feedback for addressing gesture usability concerns in cars, potential solutions from limited display devices will be reviewed and their suitability for driving feedback discussed.

This literature review finally presents different non-visual output methods for in-car information (Section 2.5) such as auditory (Section 2.5.1), tactile (Section 2.5.2), peripheral visual (Section 2.5.3), and combinations of these displays (Section 2.5). Auditory and tactile feedback are well understood to effectively present information to the driver without causing visual or cognitive distraction [49] and have been shown to be highly useful for mid-air gesture interaction [34]; however, their use in gesture interaction in cars is more limited. This is especially the case for tactile feedback, because it is difficult to deliver tactile cues when the users are not in contact with the device they are interacting with. Recent advances in technology can overcome this issue. This section discusses how tactile feedback can be delivered to the gesturing hand in mid-air using ultrasound haptics and how it can be presented to the non-gesturing hand through steering wheel feedback.

Peripheral light displays can be integrated into vehicles such as small and simple light sources like an LED strip along the cockpit door which can communicate lane change manoeuvres to the driver or approaching cyclists [53]. This review considers how others have used interactive light displays in in-car interaction and presents peripheral light feedback as a novel type of feedback for gesture interaction. It can be enriched with audio and tactile displays to create multimodal mid-air gesture feedback for in-car interaction.

2.2 Measuring Driver Distraction and Driving Performance

This section provides some background on driver distraction, the implications of driver distraction, and ways to measure it. Driving is highly demanding, which requires the driver to deal with various tasks in an appropriate and timely fashion [54]. These tasks can be divided into *primary* (driving related) and *secondary* (non-driving related) tasks. The primary task is the most important driving process as it includes navigational tasks, driving manoeuvres, maintaining a safe lane position longitudinally and laterally, as well as the perception and cognitive processing of external factors such as other participants in traffic and traffic regulations [55]. Additionally, drivers engage in secondary tasks such as eating, conversing with passengers, adjusting settings on the infotainment system for their comfort, or operating hand-held devices [56].

Anything that takes attention away from the primary task is defined as distraction [56]. The US National Highway Traffic Safety Administration categorises driver distraction into [57]:

- Visual distraction: requires the driver to take their eyes off the roads towards the source of distraction to obtain information;
- Manual distraction: requires the driver to take their hands off the steering wheel and manipulate a device;
- Cognitive distraction: occurs when the driver takes their mind off the driving task and engages it in something non-driving related such as talking to a passenger.

Driver distraction is dangerous as it directly impacts the driver's ability to control the vehicle. A rich body of research has shown that distracting activities negatively impact driving performance [58] [59, 60]. These effects include increased speed variability [61], longer reaction times and poorer car control [62, 63, 64, 65], and an increased likelihood of accidents [25]. Despite behavioural adaptations to visual distractions, such as reduction in speed [66], or greater headway to the preceding vehicles [67], it has been shown that these decrease over time, as the driver gets more used to the continued visual distractions [68].

Despite detrimental impacts of distraction on driving and the safety of any person involved, driver distraction remains a common occurrence while driving [24]. Any distraction has the potential to increase the risk of crashes and near-crashes; in particular visual distractions (e.g. looking towards the centre console screen or hand-held devices) pose a potentially greater threat to safety than purely cognitive distractions (e.g. talking, listening to music) [57]. In 2006, 30% of crashes were caused by visual distraction alone [24].

The main problem is that visual distraction does not occur in isolation; it is often accompanied by cognitive distraction. The driver needs to cognitively process the visually acquired information, leading to higher cognitive workload [67]. This is particularly important if secondary tasks are complex and require a number of steps to achieve the end goal [69]. Lee *et al.* [70] have shown the impact of the correlation between glances off the road and mental demand. Long off-road glances led to frequent steering neglects, and to overcompensation once the visual distraction ended.

The lesson is clear: long and frequent off-road glances are a safety hazard. Mid-air gesture interaction can reduce eyes-off-the-road time significantly because it is an inherently non-visual technique. Broad swipes in the air can be executed without requiring visual monitoring. This is possible due to proprioception. Proprioception is the ability to sense stimuli from within the body itself regarding movement, orientation, and position. A simple flick of the hand in air can for instance trigger a "phone call reject", eliminating the search for physical buttons on a car's centre console, consequently reducing visual and cognitive driver distraction. Supporting interaction with non-visual feedback can additionally reduce distraction by eliminating visual demands. Good feedback can help the user gesture more effectively [34] without impacting driving [38].

However, mid-air gesture interaction is a novel technique in vehicles and its impact has not been extensively measured. According to Green [71], each infotainment interface needs to be assessed in terms of driver distraction and effects on driving performance, such that the design of subsequent interfaces is informed [72] and can be improved upon.

Driver distraction can be measured via visual, manual, and cognitive distraction. Commonly used ways to measure these are 1) eyes-off-the-road time, 2) hands-off-the-wheel time, and 3) through pupil dilation [73] or through self reported workload measures such as the NASA TLX questionnaire [74]. The effects distractions have on driving behaviour are: speed variability and lane keeping ability. These can be measured through 1) longitudinal and 2) lateral car control. Finally, task effectiveness (e.g. interaction errors) and task efficiency (e.g. task completion time) are metrics to measure secondary task performance, which can be used as an additional indicator of driver distraction. These measures are the most commonly used metrics to assess distraction [56].

To summarise, driver distraction is a problem for traffic safety, as it contributes significantly to crashes and near-crash events. Multimodal feedback for mid-air gestures is a possibility for reducing these. To determine the effects of multimodal feedback, driver distraction needs to be measured such that the feedback can be improved on and distraction further reduced.

2.3 Mid-air Gesture Interaction in Cars: A Good Idea?

The discussion in Section 2.2 highlights the importance of minimising visual demand from secondary task interaction in cars. However, it is essential to understand that the number and duration of glances is defined by two parameters [38]: 1) the nature of the infotainment task requires visual attention, and 2) the driver's personal desire to engage with the device. The former is defined by the characteristics of the interface and can therefore be reduced by designing efficient displays and novel interaction techniques. The latter is defined by what the driver deems as appropriate in the current driving situation, and their own attitude and opinion towards the situation and their abilities [38].

Solutions and interfaces to dissuade the driver from looking away are an ongoing research area (e.g. [75]), however it remains in the control of the driver how much attention they dedicate to non-driving related tasks. While a touchscreen interface can be implemented in ways that discourage the need for visual attention, a driver might still choose to direct their attention towards it. Consequently, more radical solutions have to be explored which eliminate the need and the temptation to divert the eyes from the road [38].

Mid-air gestures can be a solution to eliminate visual distraction because it is an inherently eyes-free interaction technique. Research has shown that drivers prefer gesturing in air over traditional interfaces [55, 76] because they are perceived as “safe”. Mid-air gesturing can decrease visual distraction and thus increase perceived driver safety. Bach *et al.* [77] found that gesture interaction led their participants to execute fewer and shorter glances off the road compared to tactile and touch interaction; however, it was not completely eyes-free. Quick glances were still necessary to support coordination in the menu, as their design still provided visual centre console feedback. If good non-visual feedback can be provided to the gesturing drivers, visual distraction can potentially be mitigated completely.

At this point, we cannot simply say “Yes, mid-air gesture interaction in cars is a good idea” because two more issues need discussion. Firstly, careful consideration has to be applied when choosing gestures appropriate for in-car interaction. Bugl [78] has shown that gestures which require high precision over a long duration of time resulted in increased workload and distraction from the primary driving task. Therefore, the focus in this thesis is on simple mid-air hand movements, likes swipes and poses, rather than user interface controls like buttons and sliders used in previous in-car research [79, 38, 80]. Simple movements are more representative of how production cars utilise gestures and are intended to further reduce distraction, using input to simply invoke actions rather than precisely control quantities (as with sliders and dials). Finally, Riener *et al.* [2] and Jahani *et al.* [81] have shown that the primary usage for gestures should be infotainment related, as users do not feel comfortable if the execution of coarse and broad gestures in air can trigger safety critical tasks.

Gestures are a powerful mode of interaction. It is possible now to deploy technologies for sensing and processing mid-air gestures in inexpensive, mass produced items [82]. This has caused significant advances in their use from interaction with house hold appliances [5] (e.g. thermostats), smart phone usage (e.g. above device interaction), to in-car infotainment system control. The research presented in this thesis can aid the standardisation process of mid-air gesture interaction in a limited space such as the car cockpit. With the advent of automated cars, the main purpose of feedback for mid-air gesture interaction might shift from reducing visual and mental distraction to supporting the user in executing the right command in the right location

2.4 Necessity of Feedback for Mid-air Gesture Interaction in Cars

Considering human-human interaction, we communicate using gestures everyday. We use a broad range of gestures to communicate a vast amount of information, depending on the context and the culture [83]. We even gesture when we cannot see each other face-to-face such as speaking on the phone [84]. We gesture to manipulate the physical world and to explore our environment through point, grasp, touch, squeeze, and move. This strong relationship between gestures and communication has been explored in Human Computer Interaction in applications such as *Put-That-There* [85], where Bolt combined pointing and speech input to manipulate objects on a screen. He argued that an interface which allows users to utter commands along the lines of "Create a blue square . . there" and "Make that smaller . . ." can be operated more spontaneously and naturally if it is compatible with the interaction demands. The most important idea of *Put-that-there* is that it used gestures and speech together, taking advantage of their unique strengths: speech is semantically rich which makes it good for issuing commands or specifying details ("create", "blue", "square"); in contrast, pointing gestures are good for providing deictic information ("that", "there"). These deictic style commands are now used in a variety of interfaces from game console interaction such as with Virtual Reality headset and gesture controllers [86], to the Microsoft Kinect [87] and Nintendo Wii [88], to desktop computer control through the Leap Motion device [4], above device interaction with mobile phones [89], in-car infotainment control [28], to even household appliances such as TVs [90], smart taps [91], and thermostats [5].

Given this multitude of interaction possibilities, a rich body of research has emerged focusing on the usability issues of gestures. To make gesture interaction usable and understandable, feedback is necessary [82]. Users experience uncertainty when interacting with mid-air gesture systems [34], which often lack a sense of control [35]. This is partly because there are less tactile and visual cues to support interaction; for example, users lose the important feedback from physically touching a button or a touchscreen [36, 37]. Good feedback can help users overcome these usability problems by reassuring them that they are interacting correctly [36].

Feedback can be presented in a variety of ways to be as interaction and context appropriate as possible. For limited display devices such as smart watches, home appliances, and car cockpits, on-body haptic displays [92, 93, 94, 95], auditory feedback [96, 97], and peripheral lights [50, 31] are appropriate for these contexts. Limited display devices benefit from non-visual feedback because they either lack the capability to display plentiful and useful visual feedback (e.g. taps, thermostat) or it is unsuitable to do so (e.g. during driving).

Bellotti *et al.* [52] identified five usability concerns that are encountered during interaction with sensing systems:

- Address: directing communication to a system;
- Attention: establishing that the system is paying attention;
- Action: defining what is to be done with the system;
- Alignment: monitoring system response; and
- Accident: avoiding or recovering from errors and misunderstandings.

The authors proposed design guidelines for interaction with sensing systems by drawing their inspiration from how people interact with each other. While traditional interfaces for human-computer interaction seem to have well understood solutions for these concerns, gesture-based interaction still requires answers. Freeman [51] was the first to explicitly link Bellotti *et al.*'s five sensing system usability concerns to mid-air gestures. The main focus of his work was to provide feedback to support the *Address* problem in interaction with limited display devices. This thesis builds on these two bodies of work, and applies the five usability concerns to mid-air gesture interaction in driving situations. The aim is to support *Address*, *Attention*, and *Alignment* during driving. This section of the thesis will discuss the five concerns and their implications for driver safety if they are not addressed (or poorly addressed). This section will primarily review already available gesture feedback concepts in vehicles; if that is not possible, it will further discuss solutions for limited display devices such as smart watches and home appliances, because the car cockpit is an environment with limited display capabilities.

2.4.1 Address

Address concerns how a user directs their communication desire towards a system. Bellotti *et al.* [52] identified two problems when addressing a system: users need to know 1) where to gesture, and 2) and how to avoid unintentional reactions. Gesture systems also need to know when they should or should not sense, interpret, and respond to input. It is important to help the user address a system correctly and support them to direct their input towards the system. The *Address* problem is an important gesture usability challenge; if the user cannot direct their intention towards the system, then no further communication can take place.

Avoiding Unintentional Gestures

In the limited space of the car cockpit, many everyday interactions, such as reaching for a coffee mug, or gesturing in conversation should not be treated as gesture input. Accidentally addressing a system can have serious consequences, apart from annoyance and frustration [98]. Potential danger can arise for the driver when the system is activated unintentionally, and unexpectedly competes for the driver's attention [81]. Unintentional gesture recognition must be avoided if drivers are to feel confident, skilled, and comfortable with a gesture interaction system [99]. These perceived qualities are directly linked to the driver's perception of safety [55, 81] and consequently to their ability to control the vehicle.

To avoid unintentional gestures, Wigdor and Wixon [99] proposed the use of a unique activation hand pose to allow the system to interpret hand movements. Freeman *et al.* [34] and O'Hara *et al.* [100] argue that activation gestures might be unavoidable as they specify which system the user wants to address. This concept has found resonance in limited display research [5] and is thought to have potential benefits for in-car gestures [81, 98]. There is only one solution in the in-car research community which aimed at avoiding unintentional gestures [98] and it is not based on an activation gesture. Rather, the authors introduced a *dwell*; a delay of the system's readiness to interpret. Their system only started reacting to gesture input if the hand was inside the sensor's field of view for at least 500 ms. They found a decrease in false-positive recognition of unintentional gestures.

Three reasons might have prevented the introduction of an activation gesture into car gestures. Firstly, it can increase interaction duration, if the driver is firstly to grab the system's attention by executing an initial gesture, and then to execute their intended gesture. Secondly, extending the gesture vocabulary by a trigger gesture requires the driver to recall two gesture words from their memory instead of one. The user's cognitive load should be minimised, and the recall of words from the gesture vocabulary should be limited [98]. Finally, frustration regarding system usability might arise, as two gestures are required if something as simple as a skip to the next song is intended. A balance has to be found between the potential increase of driver workload due to adding an activation gesture, and the consequences of unintentional gesture input. However, as the safety of the driver is more important than their comfort, this thesis investigates the impact of an additional activation gesture for in-car gesturing.

Researchers are investing differentiation of intentional from unintentional gestures by means of machine learning tools (e.g. [101]). A machine learning algorithm gets fed a vocabulary of gesture words, and trains on hundreds and thousands of examples of these gestures. Eventually, it will be able to confidently distinguish between the words in its vocabulary and gestures which are not valid inputs. For instance, May *et al.* [98] encountered the problem where participants were unable to retract their hand from the sensor's field of view without triggering gestures. They chose to disallow input if the hand had significant backward velocity (as they did not have any gestures in their vocabulary that required backward movement). However, solutions which allow and disallow certain words enforce gestures on the user, eliminating room for exploration and creation of personal gestures. There is a large body

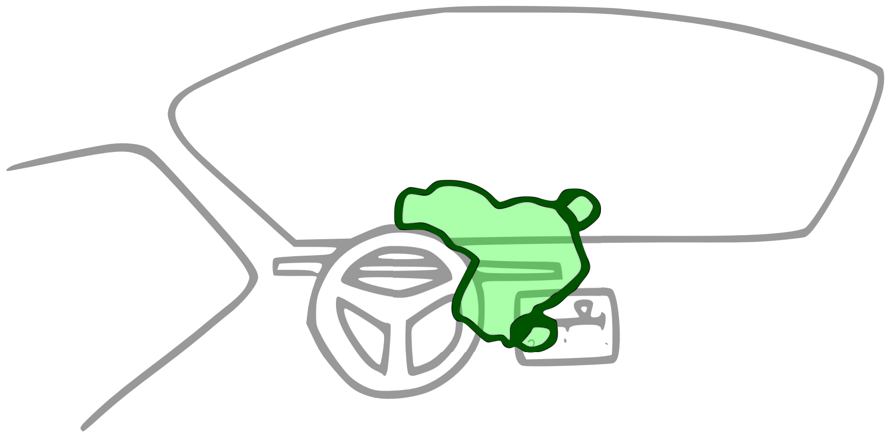


Figure 2.1: Plot of the execution area of mid-air gestures for infotainment control functions according to Riener *et al.* [2]. This area (distance = 614 cm; diameter: 547 cm) is located above the gear stick in a top right direction from the steering wheel.

of research focusing on the problem of allowing space for exploration [102] while ensuring correct gesture classification. This is a hard problem because even simple gestures such as swipe can be executed in many different ways by varying speed, duration, and angle of execution.

Riener *et al.* [2] found that, if drivers are given the space to explore and define their own gestures for functions, they have high variability between the words. One participant might use a different gesture for "increase AC temperature" than the others. The authors argue, that this heterogeneity in gesture-function mapping supports the assumption that gestures need to be user configurable. However, as this is not focus of the present thesis, it will not be discussed further.

Knowing Where to Gesture

The second aspect of address is knowing *where* to interact [34]. Users need to know where to gesture for the system to see and interpret them. If they interact outside the system's sensing area, they will not know whether the system sees them or whether they are not gesturing correctly. This uncertainty can increase glances towards the sensing area and off the road [103], as well as additional allocation of mental resources in an attempt to address the system correctly. As visual and cognitive distraction contribute to driver induced crashes, it is important to inform the driver where to gesture as they enter the sensor's field of vision. Users commonly receive feedback on entrance of the interaction area, which is called showing system attention (explained further in the next section).

Riener *et al.* [2] conducted an exploratory study showing that drivers execute infotainment control gestures in an area (distance = 614 cm; diameter: 547 cm) above the gear stick in a top right direction from the steering wheel (Figure 2.1). However, neither research nor industry

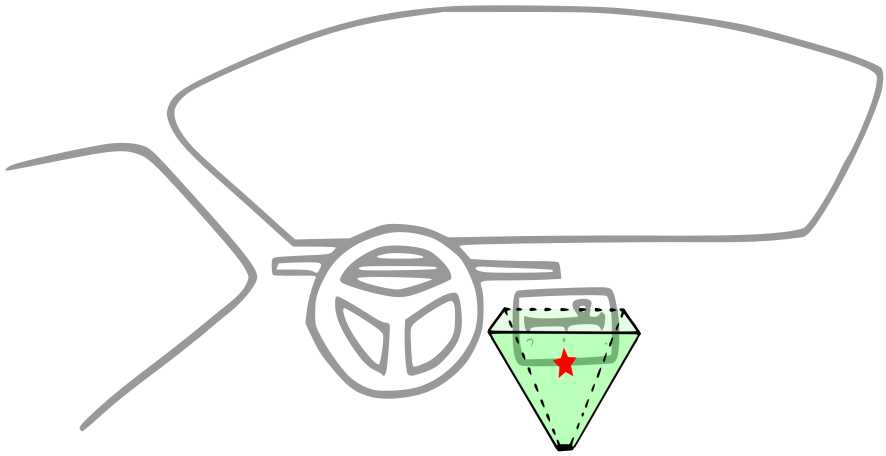


Figure 2.2: The gesture sensor's field of view is upwards facing; it is represented here via an upside down pyramid. Red star marks the sensor's "sweet spot" (i.e. optimal distance to the gesture sensor).

choose this user defined space because a large portion of the gesture area is in immediate contact with the steering wheel. Simple driving manoeuvres and hand adjustments on the steering wheel can either trigger false-positive gesture recognition if the sensor's field of view and the steering wheel overlap in space [104]; or some gestures have to be excluded from the vocabulary as they might resemble driving-related hand movements. The area above the gear stick and in front of the centre console is commonly utilised by vehicle-based gesture interaction researchers (e.g. [38]) (Figure 2.2). It is apparent, then, that there is a spatial discrepancy between the area in which the driver would prefer to gesture and the actual interaction area. Consequently, it becomes important to inform the driver where to gesture to enable effective communication between the user and the sensing system. This can be achieved by showing the driver how well the system sees them.

Limited display devices such as *Proxemic Flow* [105] and *Do that, there* [34] have looked into informing the user where to gesture by showing them how well the system sees them. Proxemic Flow interactively illuminated the floor around the users' feet with coloured light halos showing them how well the tracker sensed them. They utilised the traffic light metaphor to present a green light halo meaning sensing quality was high, and red light representing poor quality. Freeman *et al.* [34] mapped brightness of their LED strip feedback inversely (100% - 0%) to distance from the "sweet spot" (optimal distance to the gesture sensor); auditory and tactile 'Geiger counter' feedback was presented with increasing frequency towards the sweet spot. Users could use this information to adapt the position of their hand to improve gesture recognition. These studies mapped sensor data *during* gesture execution. This is referred to as *Alignment* and will be discussed further below (Section 2.4.4). This thesis will investigate how to map sensor strength feedback to the driver's hand to help guide it in air. Throughout this thesis, sensor strength can also be referred to as either the distance of the gesturing hand from the centre of the sensor's field of view, or from the interaction area's sweet spot (Figure 2.2).

Summary of Address

Two aspects of gesture usability issues can be mitigated, if the sensor system provides address feedback: unintentional input can be avoided, and the area for interaction input is made known to the user. Little automotive research has considered providing address feedback for mid-air gestures. Research is needed to develop interactions which allow drivers to direct their input towards a system, and to help them to find where to interact.

If the hand is in the centre of the sensor's field of view, frustration can be reduced as recognition accuracy increases. Frustration in a driving environment can lead to diminished perception of the surrounding events and increased crash risks [106]. Guiding the driver's gesturing hand towards the centre of the interaction area might decrease the potential for accidents by reducing negative emotional response to the gesture interface. Presenting sensor strength feedback is an effective solution for limited display device research, and can be beneficial for in-vehicle gesture interaction.

Avoiding unintentional gesture input can be achieved by introducing an activation gesture. The advantages and disadvantages of adding a word into the gesture vocabulary have been discussed. It is worthwhile to investigate an activation gesture as it has potentially greater benefits than negative impact. Further, an activation gesture and guidance of the hand towards the sensor's sweet spot can be combined into one movement. For instance, forming a fist inside the gesture interaction area could function as activation of the system, but also immediately be used to guide the user's hand towards the centre of its field of view. In Section 2.5, feedback will be reviewed which can provide appropriate in-car information for addressing a sensor system.

2.4.2 Attention

System attention concerns how the system informs the driver that it is ready and paying attention to actions. This is important, as a lack of attention feedback from the system can encourage the driver to take their eyes off the road in an attempt to understand the current problem. If the system does not show attention, then users do not know whether the lack of response to their input is due to their movements not being sensed, or if they were sensed but their input not recognised as a valid gesture. Golod *et al.* [107] suggest using multimodal feedback to show system attention, making it less likely that the user will miss it. Presenting multimodal feedback for system attention allows the driver to choose the sensory channel they want to attend to without it affecting cognitive demands [41].

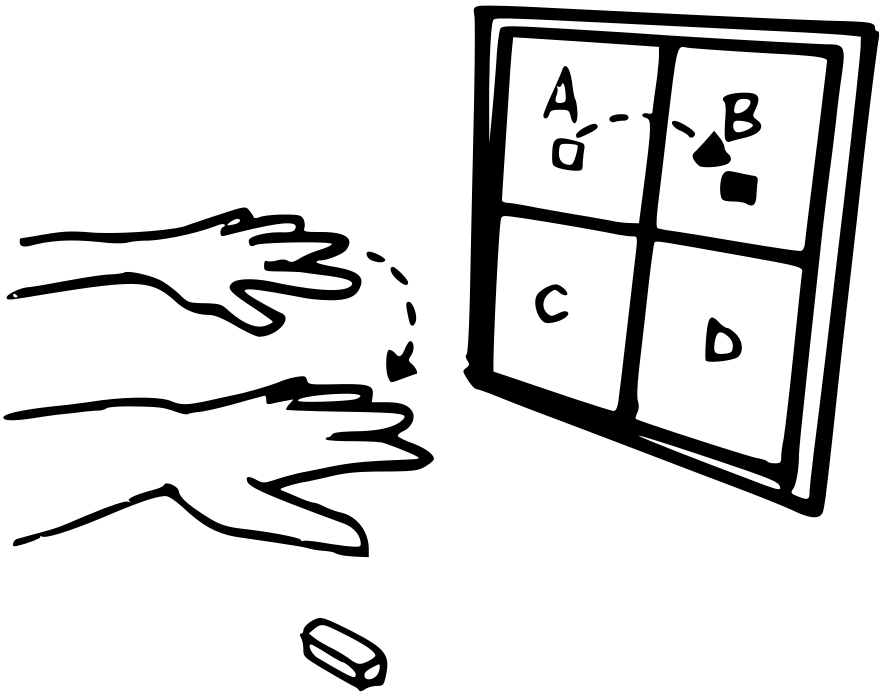


Figure 2.3: Sterkenburg *et al.*'s [3] visual feedback design. The participant moved the cursor from block A to block B by moving their hand accordingly in air. Their mid-air gesture interface utilises the Leap motion sensor and a hierarchical menu design.

Sterkenburg *et al.* [108] were the first to present system attention to the gesturing driver. They presented 2x2 and 4x4 grid layouts containing a letter in each square (Figure 2.3). As the driver's hand entered the interaction area, the centre console screen displayed a square cursor, representing the position of the user's hand within the grid, a short auditory tone was displayed in addition. System attention feedback immediately communicated to the driver, that the system "saw" their hand and was ready for further instructions. The authors of the paper argue that participants perceived the cursor in their peripheral vision which reduced the overall number of glances towards the touchscreen. This paper suggests that providing the user with the knowledge about the system's attention reduces visual distraction and cognitive distraction. However, more research is required into "showing attention" in a non-visual manner. In the above study, participants were still offered the possibility to glance towards the centre console as the screen was the primary feedback modality. However, as discussed throughout this thesis, visual feedback can be detrimental to driving safety and should be minimised for infotainment interaction, or avoided if possible.

To demonstrate system attention, it suffices to present a short message such as a "beep" [3] (audio tone), a "flash" [109] (peripheral lights feedback), or a "rumble" [36] (vibrotactile feedback on the finger via ring or on the wrist via a smart watch). These quick cues can inform the driver without distracting [44].

2.4.3 Action

Once the user knows how to address the system and whether it is paying attention to them, gesture sensing systems need to give users sufficient information about interaction so they can gesture successfully. Users need to know *which* gesture to use to achieve their goals and *how* to use them.

Which Gesture to Use

Previous research argues that it is unfeasible to have a large set of gestures in driving situations, because as the number of available gestures increases, the demand to memorise and recall also rises [110, 2, 111]. Riener *et al.* [2] found that drivers had a low intra-variability in gestures in general: they used the same gestures for different functions. Consequently, the authors recommend a maximum of four to eight different gestures for in-car interaction, since it reflects the number of driver defined gestures and is small enough to avoid extensive recalling.

Drivers still need to know which gesture to use to achieve their intended goal. Gestures can be *self-revealing* [99] through support and appropriate feedback. Revealing all available gestures however is not feasible, especially in an already demanding environment such as the car cockpit. Instead, users can be introduced to few gestures at a time, a type of *scaffolding* [99] where users are given enough assistance to support them in gradually developing skills and experience. Others have proposed selecting gestures the users already know. These include user defined gestures [2], guessable gestures [112] (which users are likely to associate with a certain action), as well as gestures that they know from different contexts [113] (such as flicking or swiping to reject a call).

It is important that interface designers find a robust and safe solution of communicating available gestures to the driver. Discovering new gestures and potentially causing unwanted system states whilst driving can increase distraction significantly [114]. A guideline for designers should be — for as long as there is no universal gesture language available — introduction to all available gestures in the interface vocabulary should be limited to a stationary vehicle. First exploration of gestures in a driving car must not be supported by the interface.

How to Use Gestures

User also need to know how to gesture, so they can interact successfully. Solutions to this problem typically include giving textual and iconic hints (e.g. *LightGuide* [115]) *before* gesture execution, and may include feedback *during* gesture interaction [116] or *after* (e.g.

Recognizer Feedback [117]). As discussed above, drivers should be experts on gesture interaction, before they drive; this thesis focuses on providing feedback *during* driving. Feedback can be presented *during* and *after* input and they can be presented *continuously* and *discretely*; these will be discussed in the following section (Section 2.4.4).

Summary of Action

Users need to know which gestures to use and how to use them. An in-car gesture vocabulary should only contain a small number of words (four to eight) to avoid increased recall demands and cognitive workload. Drivers should be taught properly how to use them to mitigate additional efforts during driving which can otherwise lead to frustration, confusion, and a decrease in confidence during interaction. Therefore, interface designers must ensure that introduction to gesture interaction is limited to stationary vehicles, and users are experienced, preferably experts, in gesture interaction before they use it on the roads. As this thesis focuses upon feedback during driving, it assumes that drivers are experts in gesture execution, thus action feedback will not be under further discussion.

2.4.4 Alignment

Another challenge of interaction with sensing systems is that users need to know how their actions are affecting the interface. Users not only need feedback regarding whether their gesture was recognised correctly, but also what effects the gesture caused. Alignment feedback concerns with *timely* and *appropriate* feedback, and how to make system *state* perceivable and persistent [52] (roughly equivalent to Norman's Gulf of Evaluation [118]). Alignment feedback concerns with providing distinctive feedback on results and on the state. Differently put, alignment is about interpreting if the system did the right thing.

For instance, during a conversation between two people, the listener gives feedback as to their ongoing understanding (e.g. nodding with the head), which is in return monitored by the speaker [52] [119]. This alignment of action and reaction supports the progress of a conversation. Similarly, users need feedback from the gesture sensing system to help them interact successfully and confidently. Timely system reaction for each gesturing action allows users to adapt their gesture (e.g. moving the hand more slowly), and informs them about their future interaction [34]. There are two types of feedback techniques to help users gesture more effectively in the future, feedback about sensing and feedback about the effects. Feedback regarding how the system senses was partially discussed above (sensor strength feedback in Section 2.4.1), which is continuous alignment feedback.

Continuous Feedback

There are two ways of presenting the effects of gesture interaction: *continuously* or *discretely* [120]. Continuous feedback is the presentation of information *continuously* throughout gesture execution. An example of continuous feedback was Sterkenburg *et al.*'s [3] study on selecting letters inside of grids (Section 2.4.2). In their study, drivers moved their hands in the air and thus moved the corresponding cursor on the screen to select a square. Once the hand/cursor entered a square, the borders of the square were highlighted contrasting it from the other squares for as long as the hand remained inside it. Both, the moving of the cursor, and the highlighting of the squares are continuous alignment feedback. It helped users navigate in the menu, but required a high amount of visual attention.

Roider *et al.* [116] also provided continuous peripheral lights feedback to gestures in cars. They mounted an LED strip on top of the dash board to show the user where their hand is located along the gesture sensor's x-axis. They found that continuous alignment feedback increased task time and visual demand of pointing gestures. Sterkenburg *et al.*'s [3] and Roider *et al.*'s [116] studies have shown that it might not be practical to display continuous feedback as it occupies a portion of attention during the entirety of the feedback duration [104]. This prolonged peripheral distraction can have an adverse impact on the awareness of traffic/road conditions, as well as encouraging the driver to remain distracted over a period of time [116]. If drivers need to repeatedly take their eyes off the road to understand their interactions with the car, then the benefits of mid-air gestures are not being fully realised.

Discrete Feedback

Discrete feedback presents the effects of gestures in finite time — not continuously during the interaction. Discrete alignment feedback for a swipe gesture can be the display of a "beep" sound to inform the driver about the transition to the next song in the play list. The user will hear that their gesture produced the intended outcome. In-car interaction benefits from discrete alignment feedback, as it informs the driver promptly about the outcome of their interaction and can thereby reduce mental and visual distraction.

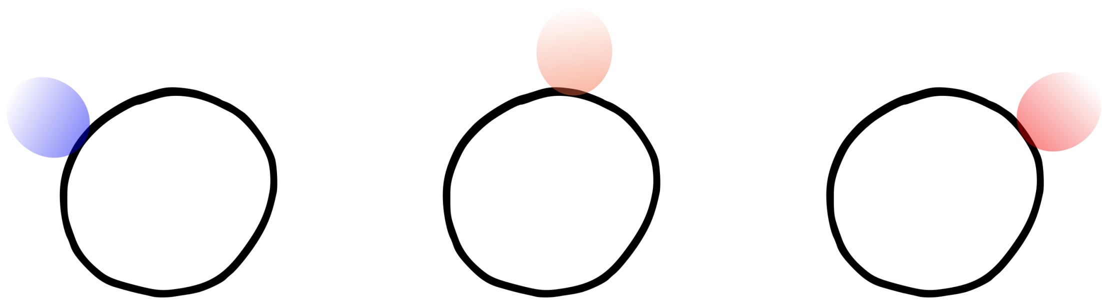
Mid-air gesture feedback research in driving situations primarily focuses on discrete feedback for alignment information. It is most commonly presented visually [113, 121, 81] or audio-visually [3, 98]. Along with centre console feedback, Sterkenburg *et al.* [3] presented speech read-outs for the currently selected target (e.g. "item A selected") and non-speech low rain drop tone for the select gesture and a high rain drop tone to confirm. May *et al.* [98] presented Spearcons (fast speech-based Auditory Icons) [122] for navigation assistance of their gesture-based menu interface, as well as non-speech audio cues for going back ('swoosh') and errors ('clunk'). Both studies presented auditory feedback in addition to visual centre

Figure 2.4: Ultrasound creation of a ball in mid-air. The hand passes through the ball and feels its edges. Box at the bottom represents the ultrasound array with 14x14 transducers. Black little box to the right is the Leap motion [4] gesture sensor. In a car, ultrasound feedback would be presented above the area where the gear stick is in front of the centre console.

console feedback. The authors reported improvements in eye glance behaviour if auditory feedback was presented, especially speech for menu item targeting. As demonstrated in the above examples, audio feedback for gesture interaction is primarily used in following ways: non-speech audio provides feedback on whether the system correctly recognised the executed gesture (e.g. “swoosh”); speech feedback gave the participant context information (e.g. “item A was chosen”), also called system state information (more about system state in the next subsection).

Tactile feedback for gestures in cars has mainly focused on ultrasound haptics [123, 38, 80, 79] which is a new but active feedback mechanism for cars. Ultrasound haptics present tactile sensations such as buttons [38, 80] and mid-air sliders [38] and dials [79] by creating small areas of pressure on the skin of the hand [124] (Figure 2.4). This feedback can reduce eyes-off-the-road time (EORT) [38], although drivers still rely on visual feedback for spatial information (e.g. where buttons were located). Like audio feedback, ultrasound haptics for gesturing in car have only been looked at in combination with visual feedback. Haptics alone however *can* successfully support mid-air gesture interaction and significantly lower task workload [36] without requiring a visual component. Freeman *et al.* [36] displayed vibrotactile information from a ring and a wrist worn device to the gesturing hand to aid in interaction with a smart phone. The changes in amplitude and roughness informed the user whether the selection of an item was successful. Their findings are promising because they demonstrate how good feedback helps users gesture more effectively. However, the driver's fashion choice should not be a determinant in whether they receive feedback in the car or not. What if the driver forgets their smart-watch? Feedback from wearables is not reliable enough for in-car interaction. Yet, this example shows that there exist haptic techniques to support eyes-free interaction for mid-air gestures. For instance, tactile information can be presented to the driver on the steering wheel (Chapter 3).

Finally, peripheral lights feedback has not found much attention in the driving community for mid-air gesture feedback even though it has been shown to support gesture interaction with limited display devices such as thermostats [5]. In that paper, participants queried the thermostat temperature setting with a closed fist gesture and they received colour coded information (blue for cool, and red for warm) lighting up the surrounding area of the thermostat. This is simple but very effective feedback as it presents clearly understandable information to the peripheral vision of the user. The thermostat temperature feedback functioned as both, discrete feedback (it was presented immediately after gesture execution) and system state feedback (colour coded the current value for temperature).



(a) (b) (c)

Figure 2.5: Examples of peripheral light supported system state feedback for three temperatures [5]. Colour and direction of the lights are dependent on the current temperature value. Left: blue for cold; middle: orange for warm; and right: red for hot.

System State Feedback

System state feedback is necessary as it tells users if and how their gesture affected the system and if they have accomplished their goal. If a gesture changes the temperature, feedback presented immediately after correct gesture execution tells the driver, that the temperature will transition to the desired degree. However, the driver does not know what the initial value of the temperature was nor what the new value will be after the modification. Users need feedback from gesture sensing systems to align their mental model of system state with the actual system state.

Most in-vehicle gesture research which provides system state feedback does so visually [3, 38, 81, 80, 79] or audio-visually [3, 98]. Visual system state feedback is usually presented either on the centre console or on the dash displays behind the steering wheel. For instance, the driver can access the current temperature setting (e.g. 19 degrees Celsius) with a query gesture and after a glance towards either screen they know immediately whether that is a temperature they will be comfortable at. Auditory feedback can provide similarly rich information by read-out information such as "current temperature is 19 degrees Celsius". Tactile and peripheral lights feedback lack the rich expressiveness of visual and audio modalities, so have not been investigated as primary system state displays for gesture interaction in cars. Yet, system state feedback can be displayed effectively through peripheral lights. Smart taps [91] and smart thermostats [5] convey system temperature setting via colour codes; blue for cold, red for warm, and anything in between as a transition from one to the other (Figure 2.5). System state can also be encoded into spatial information as in the smart thermostat example in Figure 2.5. Lights on the left of the thermostat indicate cold temperatures and lights on the right warm, and any value in-between is represented by a gradual transition of activated lights from one side to the other. The encoding of spatial information to temperature can be mapped to in-car feedback, where an LED strip along the dash can be used as a scale. If lights move from left to right, it can symbolise an increase in the current value.

Finally, tactile feedback can also successfully compensate for visual system state feedback as shown by Williamson *et al.* [125] who designed a feedback metaphor that simulates the bouncing of balls inside a mobile phone. If the user shook the phone, vibrotactile information (the bouncing balls) indicated remaining battery life. Well designed tactile feedback can result in similar performance times, perceived task difficulty, and performance success as visual feedback [93, 92, 36]. The examples given in this section show that system state information can be presented effectively through modalities such as auditory, peripheral lights, and tactile; and therefore can be a good alternative to visual infotainment feedback in cars.

Summary of Alignment

Users need to know whether the system understood their input. The alignment between the user's action and the system's reaction can be communicated with feedback. Information can be presented continuously to the user *during* gesture execution to support correct gesture interaction or inform them whether the current gesture will lead to the intended outcome. Alignment feedback can also be communicated *after* gesture execution. Discrete feedback after interaction is more appropriate for in-vehicle communication as it does not compete with the driver's workload for extended periods of time. Finally, as research [77] found, the advantages gained of limited visual distraction can be lost if system state feedback is not provided for in-car infotainment gestures. Therefore, it is important that users know the final state of the system to verify that the interaction resulted in the desired outcome.

As the reviewed literature has shown, alignment feedback is mainly communicated either visually, or audio-visually. However, providing visual information does not exploit the potential for eyes-free interaction which mid-air gestures offer. Non-visual multimodal feedback has repeatedly been demonstrated to benefit infotainment interaction and gesture interaction. Therefore, one of the key aims of this thesis is to investigate non-visual and multimodal displays for alignment feedback. If well designed, non-visual techniques can support the driver without distracting them visually or cognitively.

2.4.5 Accident

Bellotti *et al.* [52] argue that errors are an important and to-be-expected part of Human Computer Interaction and Norman [118] states that interaction between human and machine should be treated as a "cooperative endeavour where misunderstandings can happen on either side". It is important for the usability of interfaces, that users understand why unexpected system states and errors occur, and how to correct them. In driving situations, confusion about the current system state (mode confusion) or what steps to take next to recover from an error can lead to distraction [106].

Feedback can inform the user exactly what they have just done or are in the process of doing, so that they remain mentally ordered and in control of the interaction [104]. Feedback *during* action allows the user to monitor (and cancel) the task. However, since systems, unlike users, often execute an action instantaneously, it is not always possible to provide useful feedback to allow intervention during that action. More importantly, evidence presented so far has argued against feedback presentation during mid-air gesturing in a driving environment as it can increase mental workload, distract the driver, and thus impact their safety.

Solutions were proposed in the literature which help to recover from errors *after* user interaction. Mistry *et al.* [126] proposed a single "undo" gesture where the user drew an "x" symbol in air to reverse the effect of the previous gesture. Wigdor and Wixon [99] recommend two gestures, one which cancels the effects, and one which produces the opposite effect. If gesture systems will become more widespread, a universal 'CTRL+Z' gesture might emerge which can be used with every gesture system.

Feedback presentation *before* system action is usually reserved for risky operations (e.g. save, delete, etc) where designers present alert boxes to protect the users from unrecoverable mistakes [52]. However, mid-air gesture interfaces for in-car systems should not allow complex operations which require preventive measures. Mid-air gestures are simple hand movements which lack precision and can be operated in an eyes-free manner; their primary intended use is for infotainment purposes. As it is possible to recover from infotainment related mistakes, feedback presentation *before* interaction may be unnecessary.

In the driving literature, very little research has focused on recovering from falsely executed gestures. However, solutions for avoiding and correcting mistakes when gesturing may be needed less, if the usability problems discussed previously are addressed by gesture interface designers. One important aspect needs to be considered by feedback designers of mid-air gesture feedback for in-car infotainment: feedback should avoid overly attention-grabbing in error messages, as well as a negative tone because negative driver affect has been shown to impact driving performance [127].

2.4.6 Summary

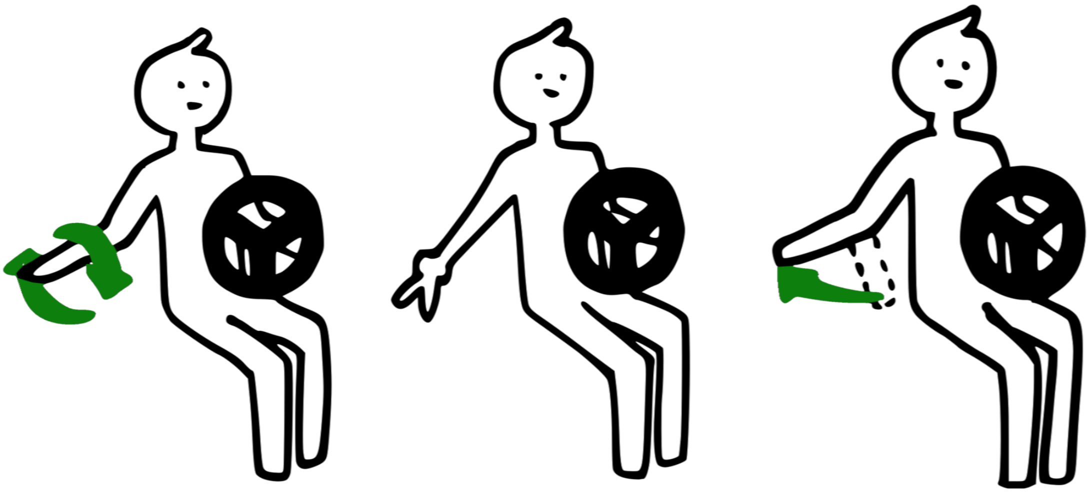
This section reviewed the usability concerns with mid-air gestures during driving and discussed current in-vehicle and limited display solutions. Despite the evident importance of non-visual gesture feedback, the literature is missing solutions which allow drivers to effectively use gesture systems. This thesis investigates ways in which gesture systems can help users overcome the *Address*, *Attention*, and *Alignment* problems.

These three concerns are perhaps the most important of in-vehicle gesture systems. Without first addressing the system, the driver would be unable to accomplish their goal. Secondly, the system needs to let the user know that it is ready and paying attention to their input. Finally, alignment feedback keeps the driver “in the loop” through appropriate system cues and helps them gesture more effectively. Drivers need to overcome these issues to gesture confidently and successfully. The sensing system needs to support the secondary infotainment interaction task, not negatively impact the primary driving task.

The other gesture sensing system problems (*Action* and *Accident*) are not focused on in this thesis. They have received some interest in the automotive research community and much more in the limited display literature. However, this thesis still makes contributions from which the other problems can benefit. Future work in these areas can build on this thesis.

2.5 Multimodal Driver Displays for Mid-air Gesture Interaction

Mid-air gestures allow drivers to operate in-car systems without reaching for physical controls which has the potential to minimise distraction [31] and improve safety [26] by replacing complex actions (e.g., precisely selecting buttons on touchscreens) with simple hand movements (e.g., swiping the hand in mid-air). The predominant hand gestures used in cars are either static hand poses, dynamic hand motion, or a combination of both [47]. Dynamic motion-based gestures, such as moving the hand horizontally or vertically, and executing circular motion, are used in most research [98, 128, 79, 116, 129, 81, 130, 131, 132], followed by static gestures such as pointing, and executing hand poses [133, 111, 134, 116, 121, 80].



(a) (b) (c)

Figure 2.6: Examples of gestures in production vehicles. Left: BMW's circular motion to to increase temperature. Middle: BMW's V-shaped hand pose to activate the infotainment system. Right: Volkswagen's horizontal swipe to skip to the next song.

Car manufacturers use both static hand poses and dynamic hand motions for their in-vehicle gesture systems (Figure 4.2). For instance, Volkswagen for instance use a horizontal swipe to skip to the next song (Figure 4.2 right). BMW use clockwise circular motion of the hand to increase temperature (Figure 4.2 left), as well as a static hand pose consisting of extended index and middle finger to activate the infotainment system (Figure 4.2 middle). Mercedes-Benz use the same V-shaped gesture for their "navigate me home" function. They further introduced functions based on the proximity of the driver's hand to a certain area. These include highlighting of media when the driver places their hand near the infotainment system, or lighting of passenger side lamps when the hand is extended towards the glove box [135].

As discussed in the previous section (Section 2.4), mid-air gestures lack critical clues which are essential in human-computer interaction: feedback. However, feedback is necessary if gesture interaction is to be successful. Current mid-air gesture systems in cars only give limited and mainly visual feedback. If drivers need to take their eyes off the road to understand their interactions with the car, then the benefits of mid-air gestures are not being fully realised. Chiesa and Branciforti [136] confirmed this by showing that visual feedback for gestures *increases* duration of off-road glances because drivers keep looking at the centre console display until they receive feedback. Therefore, non-visual feedback is ideal for in-car gestures: visual attention can remain on the road [17] whilst information about secondary tasks (i.e., interacting with the in-car systems) is offloaded to other sensory modalities [41]. In this section, multimodal displays for mid-air gestures are presented; particularly non-visual feedback modalities such as auditory and haptic feedback, as well as novel feedback in the driver's visual periphery. While most mid-air gesture research in cars focuses on designing an appropriate vocabulary to communicate efficiently with the infotainment system, they still provide some sort of feedback cues to the driver. Usually auditory and/or visual. These techniques will be discussed in turn and their appropriateness for *Address*, *Attention*, and *Alignment* problems of gesture interaction considered.

2.5.1 Auditory Displays

Auditory feedback is an effective means for communication during in-car interaction. Firstly, it is a high resolution modality which can convey complex information quickly via Auditory Icons (caricatures of naturally occurring sound) [137], Earcons (the auditory counterpart to visual icons such as brief tune or sound of a bell) [138], Speech, and Spearcons (Speech Earcons i.e.fast speech [122]). Secondly, auditory feedback conveys directional (spatial) information [43]. Unlike visual cues from the centre console, auditory cues can be received from any direction. Thirdly, it has been shown to reduce mental as well as visual distraction compared to visual feedback [139] because number of glances-off-the-road correlate with perceived mental distraction [140]. And finally, it can be implemented into existing simulators and production vehicles without additional hardware or software. This compelled initial research to focus on auditory feedback for mid-air gestures. This section discusses ways in which auditory cues were used to provide feedback for in-car interaction, reviewing speech (including Spearcons) and non-speech feedback (Auditory Icons, Earcons).

Speech Feedback

Auditory feedback can be used to deliver information in situations where additional visual loads have to be avoided or to alert the driver [141]. The majority of non-visual gesture feedback in cars use auditory cues to inform the driver whether interaction was successful. The advantage of sound is that it is possible to use language, which can convey complex information. Speech feedback has been used in in-car gesture feedback research primarily to confirm whether the system recognised the intended gesture. Akyol *et al.* [133] were one of the first to investigate gesture interaction in cars. They proposed a system which retrieves traffic news and emails via mid-air gestures. They provided speech feedback to announce the position number of the email message (e.g. "four of ten"). Bach *et al.* [77] also provided speech feedback in their study which compared the effects of tactile (dials, buttons), touch (touchscreen), and gesture interaction. Speech was provided for command verification after a gesture was executed, such as "play/pause" for a double tap in air. Additional speech audio snippets were read out if the driver gestured "get song number". Bach *et al.* mentioned that the lack of persistent system state (as it would be on a centre console) in their study design caused increased mental efforts. They argue that the lack of system state feedback can cancel out the advantage gained from limited eye glances, as it is known to be the case with speech recognition [142, 103].

Rahman *et al.* [143] provided similar speech feedback for their system as did Bach *et al.* [77]. They implemented an infotainment system where users drew symbols in air controlling the system via motion-path based gestures. Speech was used to confirm the executed gesture command (i.e. "play/pause") and on request, provided system state feedback (current media titles, etc). The focus of their contribution, similar to Akyol *et al.*'s [133], was not to measure the effects of the interaction on the driving, nor on the gesturing task, but to implement a stable gesture recognition system.

May *et al.* [98] on the other hand, measured and compared the impacts of touch and gesture based interaction on driving and visual driver distraction. They utilised speech feedback (accompanied by visual centre console cues) to give system state information ("multimedia, 8 items"). Spearcons informed the user when the selector moved to a new menu item ("three", "four", etc). The authors showed that Spearcons are an effective way of presenting rich speech feedback to gestures; and because they are shorter than full length speech output they can reduce overall interaction duration [97]. Long secondary task interactions should be avoided by interface designers and researchers as they have been shown to negatively impact driver distraction [69].

The main commonality of the reviewed work presented in this section is that speech is presented *after* gesture execution and utilised for two purposes: a) system state information (e.g. "multimedia, 8 items") and b) verification that the system interpreted the user correctly by voicing the executed command (e.g. "play"). Particularly Spearcons can be beneficial as they present rich information quickly, reducing overall interaction duration. The duration of command verification can further be sped up if non-speech feedback is displayed, such as Earcons.

Non-Speech Feedback

Non-speech feedback can provide complex information quickly through Earcons and Auditory Icons. Auditory Icons have successfully been used to convey urgency and warning messages [49] through effects like screeching tyres and of a car horn. They produce quick response times and high recognition rates [144] as well as induce a sense of urgency in users. However, attention-grabbing qualities of gesture feedback should be minimised [98] as they can distract the driver unnecessarily.

Earcons have found more application in gesture based infotainment interaction than Auditory Icons. May *et al.* [98] provided Earcons such as "swoosh" for reverse gestures and "clunk" for errors. On entrance of the hand in the interaction area, a "beep" was displayed providing *Attention* feedback. They showed, that interaction duration was decreased on average for non-speech feedback compared to speech feedback, reducing overall visual distraction significantly. Full length speech feedback is assumed to tempt drivers to glance quickly towards the centre console in an attempt to obtain (preliminary) information. However, due to their short lived-ness and not-too-attention-grabbing qualities, Bach *et al.* [77] showed that Earcons for in-car gestures can be easily ignored, missed, or misunderstood. Consequently, speech and non-speech cues are generally used in combination [98, 108, 3]: speech to provide menu navigation information and system state information; non-speech to support the user quickly and continuously during interaction.

Audio for Address, Attention, and Alignment

Bach *et al.* [77] argue for the importance of providing the user with current system state knowledge to reduce mental efforts. The user needs to remain in the loop if gesture interaction is to be efficient and un-distracting. The discussed here literature aims at supporting the driver via auditory feedback using: speech to provide system state or support the user during navigation through a menu; and non-speech to confirm gesture interaction. Contrary to speech feedback, non-speech can also be used in a continuous way. Continuous non-speech feedback can support the *Address* challenge of sensing systems by guiding movement. It can inform users how the system is seeing them by displaying sensor strength, allowing them to adjust their movements. For instance, a Geiger counter metaphor can be utilised, with increasingly faster Earcon display the closer the hand is to the interaction area's centre. Addressing an interface is a search task, and search requires continuous cues.

System *Attention* can be displayed with an acknowledgement "beep" after the hand enters the interaction area [98]. And *Alignment* feedback can be displayed in two ways: discrete non-speech cues to communicate (un)successful interaction after gesture execution; and speech cues to provide system state knowledge. This thesis has repeatedly argued against the usage of continuous *Alignment* feedback whilst gesturing in cars because it has been shown to be overwhelming and distracting [116].

2.5.2 Tactile Displays

Haptic and tactile feedback will be defined as follows for the remainder of this thesis: *Haptic* feedback is information which is received by the *cutaneous* sense from the skin (also referred to as tactile feedback), and the *kinesthetic* sense, which is information sent from internal stimuli (receptors in muscles, tendons and joints) indirectly caused by external stimuli such as movement of a limb [145, 146]. *Tactile* feedback is the kind of sensation that is

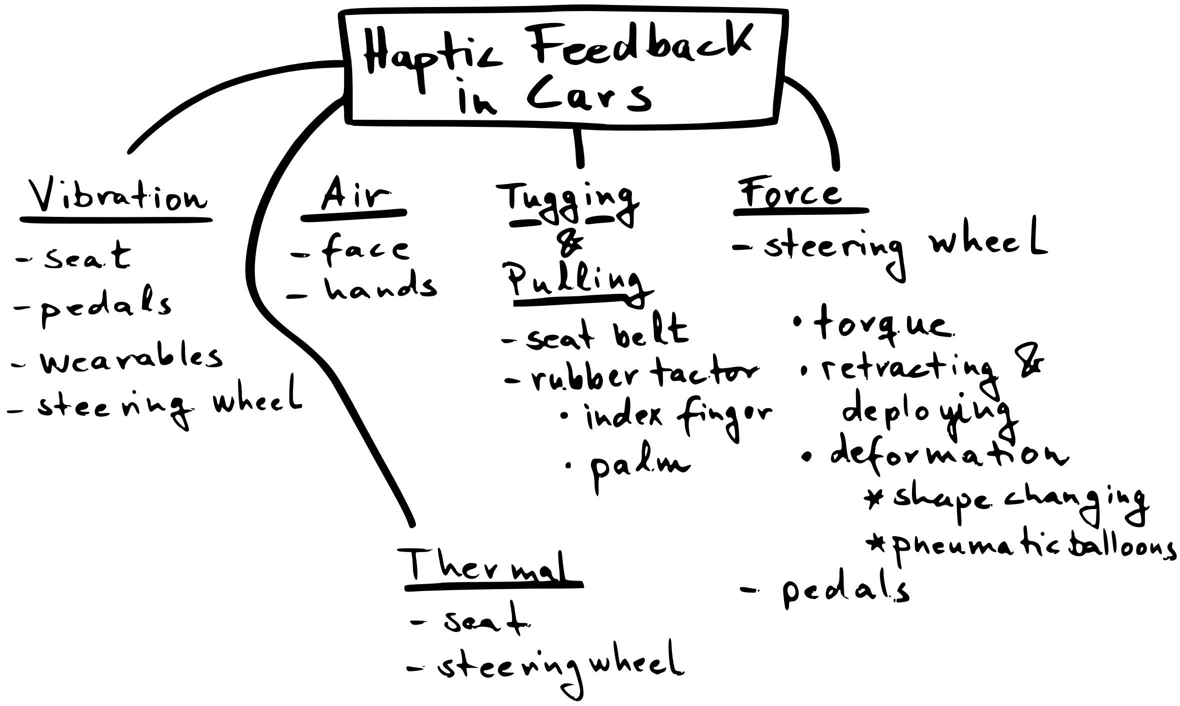


Figure 2.7: Different techniques of presenting haptic feedback to the driver.

sensed primarily by the skin's sense of touch (cutaneous) from stimuli such as vibration and temperature. It is generally less forceful and limited to the surface of the skin [147, 148].

In a driving environment, haptic feedback can be presented in multiple ways (Figure 2.7): 1) vibration through a) the seat, b) the pedals, c) the steering wheel, d) wearables; 2) air streams to a) the face, b) the neck, c) the hands; 3) tugging and pulling of a) the seat belt, b) skin on the fingers and palm; through 4) shape changing steering wheels which a) retract, b) balloon, and c) change shapes; 5) force a) through torque in the steering wheel, and b) pedal; and 6) thermal feedback in the a) steering wheel and b) seat.

Tactile feedback is a core part of providing 1) a sense of agency to the gesturing driver [35] whilst 2) reducing eyes-off-the-road time [38], and 3) distributing secondary task information to a non-visual channel [48, 42]. Ho *et al.* [43] have shown that tactile cues capture a driver's attention quickly and accurately, demonstrating potential for robust message delivery with no additional cognitive demand, nor impact on driving performance. The hands are the obvious medium for tactile message input in a driving environment, because they have the second highest tactile acuity (following the face) [149]. This section investigates the display of tactile information a) to the non-gesturing hand via steering wheel feedback (Subsection 2.5.2); and b) to the unadorned hand gesturing in mid-air through ultrasound haptics (Subsection 2.5.2).

Steering Wheel Feedback

Research has investigated several ways of using haptic feedback from the steering wheel to present information to drivers. Information has been presented using vibration [11, 12, 13, 14, 15, 16], thermal signals (warming or cooling the wheel) [8], torque [15, 150, 151, 152], and steering wheel deformation [9, 7, 6, 10, 153, 154]. This subsection discusses these approaches and reflects on what characteristics make for effective information presentation from the steering wheel.

The main advantage of steering wheel feedback is that tactile notifications can be displayed to the hands while allowing the driver to adhere to the "eyes on the road, hands on the wheel" [142] paradigm for safe driving. Vibrotactile steering wheels have received the most attention [11, 12, 13, 14, 15, 16] since they provide instantaneous and familiar feedback to the driver. This is important in order to avoid long interaction and increased mental workload [69]. Hwang et al. [11] proposed a vibrotactile steering wheel with 32 linear actuators embedded into it. These actuators presented information such as *alert*, *turn left*, and *turn right* to the driver with high pattern recognition rates between 88% to 93%. Kim *et al.* [16] embedded 20 vibrotactors into the steering wheel and activated them in either clockwise or anticlockwise patterns. These two studies report high pattern recognition rates and significant improvements in driving performance when vibrotactile feedback was provided. Kern *et al.* [14] embedded six vibrotactors into the wheel and reported that their participants struggled to identify the origin of the stimulus. The problem was, that vibration spread throughout the entire rim and thus blurred its origin. In an attempt to mitigate vibration spreading through the rim, Enriquez *et al.* [6] implemented "pneumatic bladders" over vibrotactile tactors [155]. Changes in shape and configuration of the pneumatic bladders allowed for a variety of vibrotactile and kinaesthetic patterns. Vibrotactile stimulation of a single bladder did not interfere with the sensing of the next bladder, thus enabled localisation of stimulus origin. The authors reported slow reaction times, but mentioned that the pneumatic balloons can be utilised to inform the driver of problems otherwise unnoticed. Many other vibrotactile steering wheel approaches have reported a blurring of the origin of stimulus, e.g. [15, 14]. However, research has shown the importance of presenting information spatially (i.e. to each hand) because it results in robust message acquisition as it captures the driver's attention effectively [156] with no additional mental demand. Another challenge of vibrotactile messages is that while they have been shown to have high recognition rates during a primary task, their effectiveness suffers significantly in multitasking environments such as during driving [157]. Perception accuracy can further decrease if natural in-car vibrations mask the stimulus [15]. Finally, participants perceive vibrotactile feedback from steering wheels as urgent [158]. As May *et al.* [98] pointed out, gesture feedback should not be too attention grabbing because it can distract the driver unnecessarily.

Ergo, non-vibrotactile steering wheels have been investigated. Enriquez et al. [6]'s pneumatically inflatable balloons also provided kinaesthetic information by inflating and deflating, however the range of haptic information was limited (more in the range of binary). Other problems associated with pneumatic balloons are air leakages, and that they are bulky and hard to control [159, 155].

Medeiros-Ward et al. [10] investigated the usability of tactile shear cues to the index finger from a "sandpaper-like rubber tactor" on the steering wheel. This button deformed the skin in different directions to give navigation cues. Their approach was successful but had limitations: it only facilitated directional tasks; no additional information was displayed. Furthermore, they did not test whether the tactor affected driving performance.

Torque (force) feedback can remain unnoticed since it can be mistaken for driving related ("natural") torque caused by the road or the tyres [150]. Borojeni *et al.* [9] proposed a torque-like steering wheel for level 3 of automated cars (limited self driving [160]). They tested a steering wheel with moving surfaces under the driver's palm. These surfaces hinted the steering direction after the driver took over control. They found, that participants felt reinforced in their decision to manoeuvre in a certain direction if the moving surfaces also pointed towards that direction. Mok *et al.* [7] also proposed a force feedback steering wheel for partially and fully automated cars. Their steering wheel solution deploys from the dash board as a take over request. In their simulated driving study, they demonstrated a substantially reduce crash risk compared to a conventional steering wheel.

Di Campli San Vito *et al.* [8] were the first to investigate thermal feedback for navigational purposes. They installed two peltier devices on the steering wheel under each palm of the driver. Thermal feedback was presented to the turning direction and showed promise with 94.2% correct recognition of warnings 200 metres before the turn and to 91.7% correct turns. The temperature changed from the neutral 30°C by 6°C, with a rate of change of 3°per second. This feedback technique is useful for non-critical applications due to the limited amount of presentable information.

To summarise, pneumatically inflatable balloons only provide limited information [6]; thermal feedback is time costly [8]; and "sandpaper-like rubber tactor" [10] provides tug and pull information to the index finger, which is primarily useful for navigational tasks. Shape-shifting steering wheels, as presented in [9] and [7], are also only useful for limited information: such as maneuvering after regaining control over the automated car [9]; or for binary messages regarding safety critical systems [7] through a retractable and deployable steering wheel.

On the one hand, there are vibrotactile steering wheels which can convey a large amount of different messages through varying tactile patterns [11, 12, 13, 14, 15, 16], however at the cost of loss of spatial information. On the other hand, there are force feedback steering

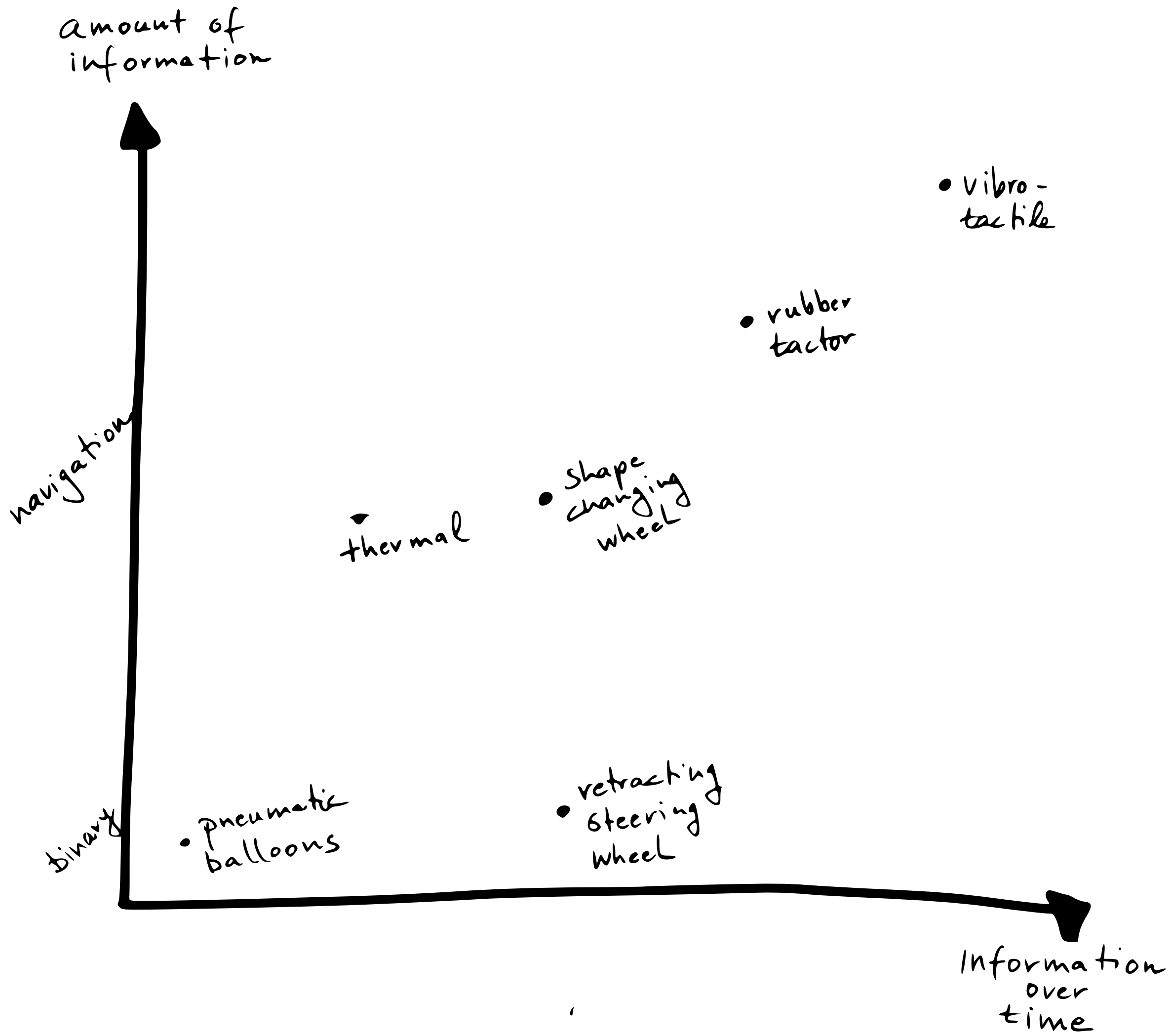


Figure 2.8: Summary of steering wheel feedback presented in the literature. Pneumatic ballons [6]; retracting steering wheel [7]; thermal [8]; shape changing [9]; rubber tactor [10]; vibrotactile [11, 12, 13, 14, 15, 16]

wheels which can convey spatial information with high accuracy, however at the cost of increased information density [10, 9, 7, 6]. There seems to be a gap in the steering wheel feedback literature for a technique which 1) delivers rich messages, 2) maintains high spatial accuracy, 3) conveys robust cues (unmistakable for natural torque or in-car vibration), and 4) presents them quickly. These four aspects are important for mid-air gesture feedback. Feedback designed to support mid-air gesturing in cars needs to be distinguishable (points 1, 2, & 3) to avoid user confusion and additional cognitive resources to decode them, and they need to be presented in a timely fashion such that the user understands the feedback as reaction to their executed command.

Therefore, this thesis presents a novel feedback technique namely *Cutaneous Push feedback* (Chapter 3) to close this gap. However, Cutaneous Push feedback's efficacy for infotainment notifications has to be tested before it can be considered for mid-air gesture interaction; thus Research Question 1 was informed:

> **RQ1:** How effective is Cutaneous Push feedback from the steering wheel to the driver's palm (*Studies 1, 2, & 3*)?

Mid-air Ultrasound Feedback

Ultrasound haptics is an alternative feedback modality for message delivery to the hand. Focused ultrasound creates areas of acoustic radiation pressure which make haptic shapes [161, 162, 163] and patterns [164, 165] perceivable on the skin of the hand. It provides information to the unadorned hand in mid-air, increasing a sense of agency [35] and reducing visual distraction during gesture interaction [38].

Prior to the work in Chapter 5 (published in 2018 [166]), the impact of ultrasound feedback for gesturing had not been investigated, neither on driving performance, visual and cognitive distraction, nor secondary task performance. This is a timely problem, as some production vehicles (e.g. BMW, Jaguar Landrover) use ultrasound haptics for gesture interaction with their in-car systems. BMW presented ultrasound feedback for mid-air buttons [80], the ultrasound array developing house *Ultrahaptics* use their device for feedback for in-air dials [79], and Jaguar for buttons and sliders [38, 123]. In these three studies, Ultrasound was accompanied by visual and/or auditory feedback. Harrington *et al.*'s [38] results showed, that ultrasound feedback reduced EORT significantly compared to visual feedback only.

As mentioned above, ultrasound feedback can be beneficial to mid-air gesturing in cars, however it comes with many challenges. For instance, Rutten *et al.* [162] investigated the perception performance of different shapes and found that vertical and horizontal lines (51% and 50% correct recognition), hand scans (60%), and dials (54%) were recognised with highest accuracy. These numbers show that ultrasound technology is not yet advanced enough to

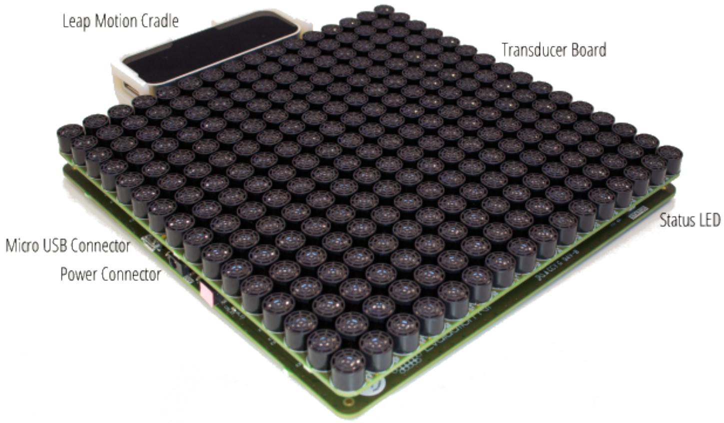


Figure 2.9: Ultrahaptics' ultrasound array.

present patterns and shapes with great recognition accuracy ([162] published in May 2019). Rutten *et al.* further found a "strong decline in [shape perception] accuracy related to age". However, age related decline in sensory perception can be overcome if feedback is presented multimodally [167]. Generally, presentation of feedback to multiple sensory channels during driving has been shown to improve perception whilst decreasing mental demand [156]. Non-visual feedback can support infotainment interaction during driving. Ultrasound haptics can potentially be improved through multimodal feedback.

Mid-air Ultrasound Feedback for Address, Attention, and Alignment

The ultrasound array's display area (width: 14 cm; depth: 14 cm; height: 10-15 cm) is smaller than the Leap motion's interaction box area (width: 23 cm; depth: 14 cm; height: 23 cm) (Figure 2.10). Thus, it might not be necessary to guide the user's hand towards the interaction "sweet spot" because once the driver perceives ultrasound feedback on their hand, they can be sure that they are within the sensing area. This requires, however, that *Attention* feedback is presented. A short tactile pulse against the centre of the palm can suffice to inform the user that the system is "seeing" them . *Alignment* feedback for simple gestures and hand poses can be lines, hand scans, or circles as these have been shown to have the highest perception accuracy [162].

2.5.3 Peripheral Light Displays

Screens are the predominant way of presenting information to drivers in cars, e.g., the central console screen and navigation devices placed near the dashboard, dials and displays behind the steering wheel. These are commonly used to present interaction feedback, although this

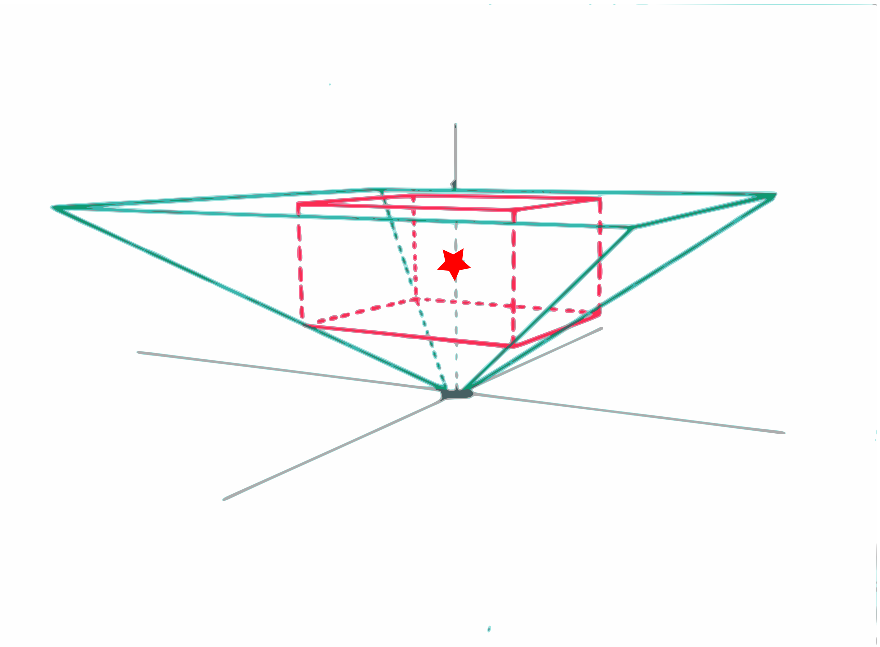


Figure 2.10: Leap motion device (origin of coordinate system), its sensing area (green or upside down pyramid), the Ultrasound array's display area (red), and the "sweet spot" (red star). Image inspired from the Leap motion developer site.

is not ideal for driving scenarios: a driver's visual attention should be on the road. An alternative to screens is to present visual information using low fidelity displays within the driver's visual periphery, so that it can be seen whilst focusing on the road.

Peripheral displays are effective in demanding environments such as aeroplane cockpits because they do not interfere with the primary task [168]. Nikolic *et al.* distributed several LEDs in an aeroplane cockpit such that they displayed signals to the pilots' peripheral vision. They showed that simple LED lights in the periphery are an effective and feasible solution to convey information in data driven environments with no additional cognitive demand [169, 170].

These findings have led to growing interest in ambient light feedback in driving situations. *AmbiCar* [17] was the first interactive lights display used in a car to inform the driver about driving related events [53]. LED strips were embedded along the front left door, the A-pillar, the steering wheel, the rear mirror, and along the dashboard up to centre console (Figure 2.11). Löcken *et al.* have used peripheral visual cues to inform drivers about safety distance violations [171], lane change decisions [172], current travel speed [173], and the intentions of an automated car [53]. Results from these work shows that, if designed well, peripheral lights demand significantly less visual and cognitive attention than a traditional centre console screen.

Peripheral lights have also found application in gesture interactions. *Comrade* [113] is a concept car which negotiates control between the user and the autonomous vehicle through

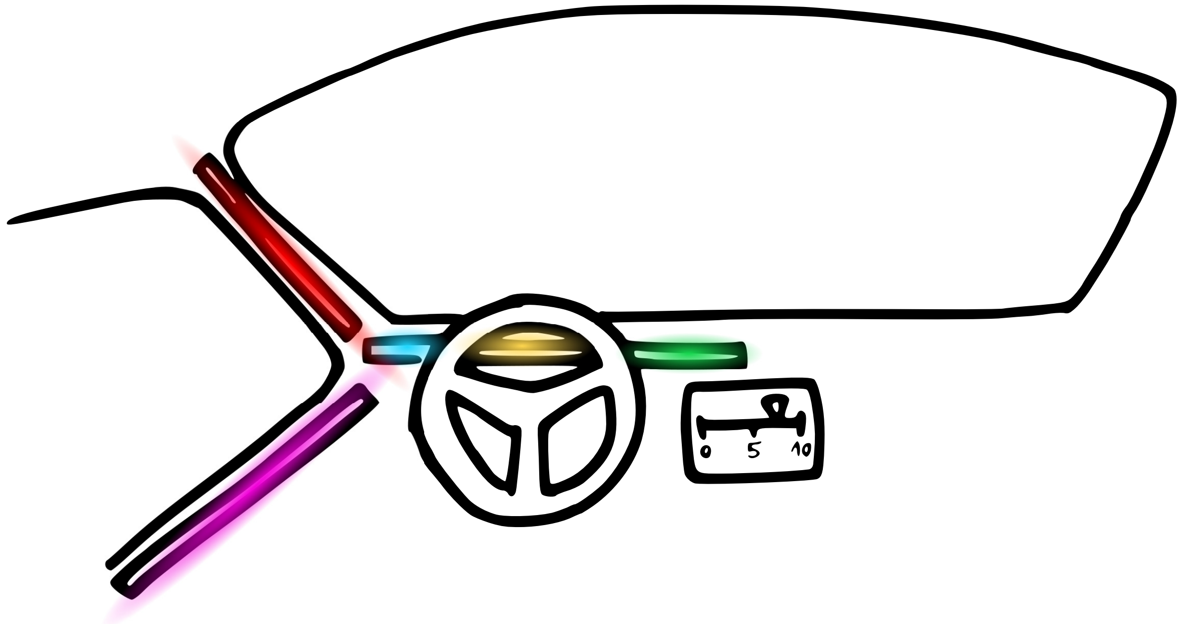


Figure 2.11: Peripheral lights feedback along the front left door, the A-pillar, and the dashboard up to centre console [17].

peripheral lights and sideways hand gestures. An LED strip along the dashboard (from A-pillar to centre console) indicated the willingness of the system to hand over control. If the user gestured for the car to take over control, but the system refused to do so, lights turned red. This is an effective example of alignment feedback. Simple light animations in the driver's periphery can be highly informative without requiring full visual attention.

Subsequent to the work in Chapter 4 (published in 2017 [31]), Roider *et al.* [116] implemented peripheral light displays for pointing and swiping gestures. The pointing gesture allowed the driver to select points of interest in their field of view; peripheral lights feedback continuously visualised the pointing target with a small light bar. A light bar was faded in at the beginning of a swiping gesture, grew opaque and into the direction of the swipe gesture. Both feedback types were presented continuously during the gesture interaction. The authors reported that the pointing gesture accuracy was increased due to the cost of longer task duration and increased visual demand. Freeman *et al.* [34] showed that peripheral lights in combination with tactile feedback can successfully overcome the shortcomings of each feedback type and provide an additional modality for mid-air gesture feedback for mobile phones. Therefore, if combined appropriately, peripheral lights are promising for in-car gesture applications.

Peripheral Lights Feedback for Address, Attention, and Alignment

For *Address* concerns, more specifically *knowing where to gesture*, peripheral lights can map the distance of the driver's hand to the interaction "sweet spot" inversely with brightness (light becomes brighter the closer the hand traverses towards the system's sensing centre) [34]; *Attention* can be presented by a short dim pulse of the LED lights; and *Alignment* feedback for correct gesture execution can be a fast animation of colour coded lights *after* successful gesture execution. Finally, system state feedback can be presented if the LED strip behind the steering wheel (Figure 2.11) functions as a scale. A half-filled LED strip can indicate 19 degrees Celsius, and each gesture can progress the lights towards the right (filling up the strip) symbolising an increase in temperature.

2.5.4 Head-Up Displays and Augmented Reality

Head-Up displays (HUD) project information on the windscreen and can reduce duration and frequency of off-road glances [174]. The HUD can be defined as any transparent display which presents data to the driver without requiring them to take their eyes off of their viewpoint [175]. Augmented Reality (AR) can also be used to display information onto the screen, however, the presented elements (e.g. arrow) match the real road scenery (Figure 2.12).

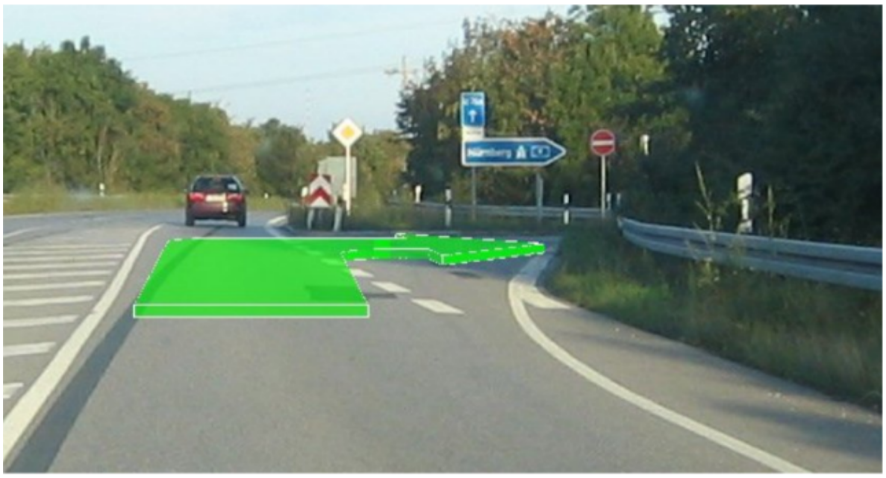


Figure 2.12: Head-Up Display with Augmented Reality aimed at supporting the driver in navigational tasks [18].

There are many benefits of HUD over traditional Head-Down Display (HDD) with the main being that the head-up location is expected to allow the driver to keep their gaze on the road, more than the HDD. This benefit is achieved by reducing the time the eyes need to re-focus from the external visual input to in-car infotainment system cues [176]. HUDs further enable shorter glance distances which improves EORT [177] thus allowing for more time to scan the traffic scene. This results in quicker reaction times to external road events, earlier detection of road signs, less mental stress for drivers and they are easier for first time users [178, 174]. Gish *et al.* [179] argue that the increased situation awareness enabled through HUDs can impact the probability of successful detection of time-critical events.

Despite all these benefits, HUDs still require extensive research in order to fully understand under what conditions they add value [174, 180]. Smith *et al.* [180] found that HUDs were associated with significantly faster task performance but contributed to more secondary task errors. Oh *et al.* [181] measured the impact of the semi-transparent objects superimposed on the windscreen (augmented reality (AR)) on visual distraction between older and younger groups. They found that with an increase in superimposition, an increase in driver glance duration was found independent of age. HUDs and AR can further occlude potentially dangerous objects and events on the road; for instance, it is hard to tell via a quick glance whether the arrow in Figure 2.12 covers an object or not.

Iavecchia *et al.* [182] found that if the eye is focused on the HUD, objects in the outside world appear smaller and more distant than they factually are. Roscoe [183] argues that this can lead to the overestimation of the distance to objects and increase the likelihood of crashes and near crash events. Finally, HUDs still present visual information to the driver. Multiple visual stimuli — especially textual information — have been shown to capture the drivers attention [184].

Pauzie [174], Smith *et al.* [180] and Oh *et al.* [181] argue that HUDs can be beneficial; however, the interface has to be carefully designed and the negative effects of HUD use need to be considered when implementing this technique. HUDs and AR are viable avenues of research; however, since this thesis aims at minimising visual distraction, HUDs and AR were not considered as a feedback modality because they can increase glances off the road.

2.5.5 Olfactory Feedback

Olfactory feedback for in-car interaction has gained a new momentum in the past few years [185, 186, 187, 188]. Olfactory stimulation has been shown to have positive effects on the alertness [189] and the mood of the driver [190], drivers' braking performance [191], keeping drivers awake [192]; and it has shown to be beneficial to drivers as it can influence their emotions, relax them, and lighten their mood [193]. Castiello *et al.* [194] argue that scent stimulation can reduce visual overload, thus it can be beneficial to in-car interaction [185].

The sense of smell is a very powerful medium [195] and therefore, can enable the extraction of meaningful information [196]. For instance, smells and odours trigger automatic and implicit retrieval of information related to the object the scent is coming from (e.g. the grasping movement is greater when an orange scent is presented compared to the scent of strawberries) [194]; they allow automatic access to terms which are semantically related to odours (e.g. smelling citrus-scented all-purpose cleaner enabled faster recall of cleaning-related words than other words) [197]. And as modern vehicles are already equipped with hardware necessary for olfactory stimulation (e.g. ventilation system) [185], there is a viable research avenue for olfactory feedback as a new semantic layer to in-car interaction [187]. However, olfactory stimulation is a challenging communication channel for in-car interaction [187] due to the slow decay rate of the scent and interpersonal differences [188]. Therefore, it is impractical for gesture feedback; the driver requires immediate updates about the in-car system, what their gestures commands have triggered, and what new system state has been reached. As this thesis aims at supporting the driver during mid-air gesture interaction, olfactory feedback will no longer be discussed.

2.5.6 Multimodal Combinations of Driver Displays

The context in a driving situation can change quickly. If a driver passes construction works, auditory feedback might be drowned out; a sunny spell after heavy rains can reflect very brightly and render visual feedback ineffective; and a bumpy road can mask tactile feedback. Hoggan *et al.* [198, 199] argue that "as the context changes, so should feedback modality" and a large body of work supports this. A plethora of studies have used multiple modalities for in-car interaction and consistently found improvements over unimodal feedback. Multimodal feedback reduces mental demand [41], reaction times to cues [42], whilst supporting driving [46] and infotainment interaction [123, 38]. Presenting information redundantly to multiple sensory channels supports eyes free interaction [200] because it provides confirmation — a *reinforcement of perception* [14]. It allows the driver to use the most appropriate sensory channel for information throughput [198, 199]. Multimodal feedback is also perceived as less cognitively demanding compared to unimodal feedback and thus preferred by drivers [42, 45, 14, 46, 47, 48]. Older adults particularly benefit from multimodal feedback as sensory acuity decreases with age [201]. Multimodal stimuli have been shown to restore response times of older participants to those of young participants reacting to a single stimulus. These findings suggest that multimodal feedback can compensate for age related sensory degradation [167]. This thesis investigates the efficacy of novel, non-visual multimodal feedback for mid-air gesture interaction in cars.

2.5.7 Summary

This section reviewed non-visual output modalities for mid-air gestures in cars and discussed state-of-the-art driver displays. Feedback modalities such as Auditory, Tactile, and Peripheral Lights discourage drivers from looking at the console screen and therefore are worth investigating. Whilst potentially able to convey less detailed information than a high resolution screen, non-visual cues have been shown to successfully support input. However, the lack of research into non-visual, unimodal feedback for in-car gesture interaction has motivated the following research question:

> **RQ2:** How do *unimodal* mid-air gesture feedback techniques influence driving performance and in-car interaction (*Study 4*)?

Multimodal combinations may increase the efficacy of unimodal output, supporting successful gesture interaction without affecting driving. Multimodal feedback is beneficial for gesture systems and in-car information systems. It can reduce mental demand, reduce visual distraction, and assure users they are interacting correctly. This motivated the research questions:

> **RQ3:** How do *multimodal* mid-air gesture feedback techniques influence driving performance and in-car interaction (*Study 5, 6, & 7*)?

Research questions **RQ2** and **RQ3** measure the impact of feedback on straight driving, attempting to obtain a clean measure of the impact of gesturing and feedback modality on car control. The following research question investigates whether these results also apply in more challenging driving. It is important to test the multimodal feedback designs in a range of driving scenarios to test their performance under differing levels of cognitive demand.

> **RQ4:** What effect does multimodal mid-air gesture feedback have on more *challenging driving* (*Study 6 & 7*)?

2.6 Conclusions

This chapter discussed available literature on three topics in order to motivate the research questions for this thesis. Section 2.2 presented background on driver distractions, their causes and implications for safety. Mid-air gestures can reduce infotainment related driver distraction, but as highlighted in Section 2.4, it is important that sensing systems provide feedback to support interaction. Section 2.5 presented studies on non-visual feedback modalities. A set of studies on tactile steering wheel displays revealed the lack of a single technique which can deliver messages efficiently to a driver's palms. This informed the novel steering wheel feedback technique *Cutaneous Push* (Chapter 3). Research is needed to understand the effectiveness of this type of feedback, informing research question:

> **RQ1:** How effective is Cutaneous Push feedback from the steering wheel to the driver's palm (*Studies 1, 2, & 3*)?

The results from **RQ1** and findings from Sections 2.4 and 2.5 were used to inform research question:

> **RQ2:** How do *unimodal* mid-air gesture feedback techniques influence driving performance and in-car interaction (*Study 4*)?

Finally, *multimodal* combinations of feedback may increase the efficacy of unimodal output, supporting successful gesture interaction without affecting driving. It remains to be investigated whether multimodal output benefits *simple* and more *challenging* driving. This motivated the research questions:

> **RQ3:** How do *multimodal* mid-air gesture feedback techniques influence driving performance and in-car interaction (*Study 5, 6, & 7*)?

> **RQ4:** What effect does multimodal mid-air gesture feedback have on more *challenging driving* (*Study 6 & 7*)?

The remainder of the thesis will answer the above research questions. Evidence discussed so far has shown that tactile feedback is an effective feedback channel for eyes-free interaction with a mid-air gesture system. However, as it became evident in the previous sections, there is a gap in the steering wheel feedback literature for a technique which delivers 1) rich messages, 2) maintains high spatial accuracy, 3) conveys robust cues (unmistakable for natural car vibrations), and 4) presents them quickly. These four attributes are important if tactile feedback from the steering wheel is to support mid-air gesturing in driving situations. Feedback designed to support mid-air gesturing in cars needs to be distinguishable (points 1, 2, & 3) to avoid user confusion and additional cognitive resources to decode them, and they need to be presented in a timely fashion such that the user understands the feedback as a reaction to their executed command. Therefore, this thesis presents a novel feedback technique namely *Cutaneous Push feedback* to close this gap. Research in Chapter 3 investigates the efficacy of this novel feedback technique from the steering wheel to the driver's palm. It shapes the basis of how to present and use Cutaneous Push feedback, which informs its use for mid-air gesture interfaces in research discussed in later chapters in this thesis.

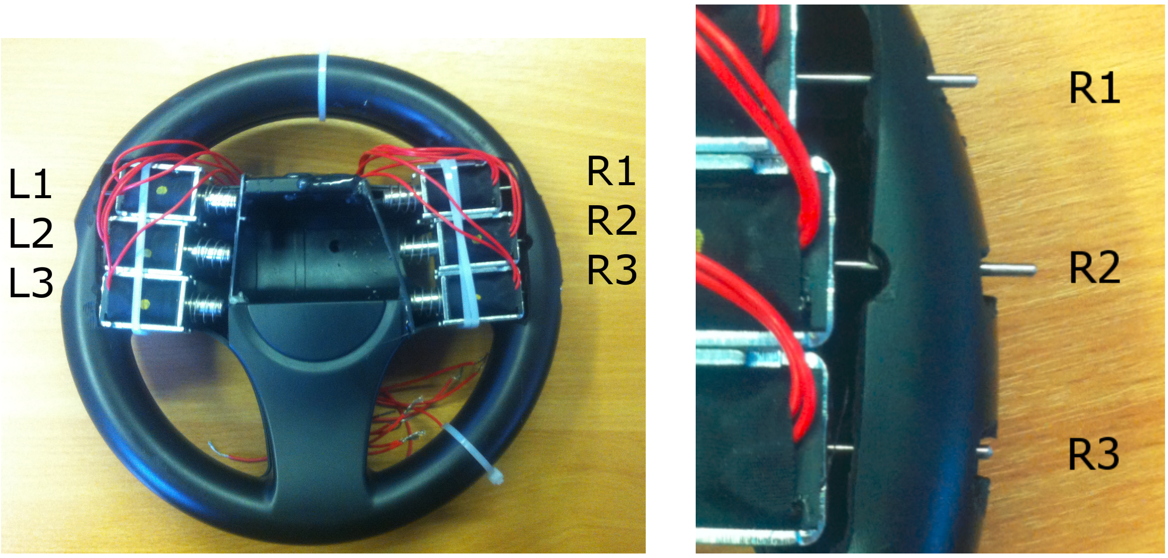
Chapter 3

Cutaneous Push Feedback from the Steering Wheel

3.1 Introduction

Users need feedback when interacting with gesture systems. Particularly the lack of tactile feedback is a core part of user uncertainty [35, 36, 37], which can lead to drivers taking their eyes off the road [38]. Good feedback can overcome these issues. The literature discussed in Chapter 2 revealed that previously investigated haptic feedback on the steering wheel is time consuming, offers only a small vocabulary, or lacks spatial information. However, it is essential for good feedback in driving situations to be delivered *instantaneously*, whilst retaining *spatial* cues and to be *diverse* enough to convey different information.

This chapter introduces Cutaneous Push feedback which provides instantaneous, rich, and spatial information on the steering wheel to the driver. This is achieved through six actuated solenoids embedded into the rim of the steering wheel (Figure 3.1). Three solenoids are embedded under each palm and create cutaneous force feedback. The six solenoids allow for a broad range of tactile messages consisting of 64 (six pins with two states of *in* and *out*: $2^6 = 64$) static patterns and at least 20 dynamic patterns. These messages further encode spatial information by providing push feedback to different locations on each palm, and spatial information across both hands. Finally, the solenoid pins can protrude within 50 ms seconds and thus provide instantaneous tactile feedback to the driver. Therefore, Cutaneous Push feedback bridges the identified gap in the literature and presents *rich* information which can be delivered *rapidly* while maintaining *spatial* information. Since this is a novel feedback technique, little is known about the efficiency and perceivability of Cutaneous Push patterns presented using six solenoids, particularly when driving. This chapter aims at answering the following Research Question:



(a) The Cutaneous Push steering wheel with six solenoids embedded into it (three on each side). The nomenclatur of the solenoids is according to position on the steering wheel, e.g. bottom left solenoid is L3.

(b) Enlarged right side of the steering wheel. R1 and R2 are activated and are pushing out. R3 is not active.

Figure 3.1: First Cutaneous Push steering wheel. Solenoids were embedded into the rim of a Nintendo Wii steering wheel. A latex sheet covered the entire surface of the wheel to enlarge the contact area with the user's hands.

> **RQ1:** How effective is Cutaneous Push feedback from the steering wheel to the driver's palm (*Studies 1, 2, & 3*)?

This chapter describes three experiments which investigate (1) the perceivability of a variety of Cutaneous Push feedback messages to the palm; (2) the characteristics of the feedback patterns which result in best/worst recognition performance; and (3) whether Cutaneous Push feedback affects driving performance. Study 1 introduces Cutaneous Push feedback for the first time. The actuated surface was realised by embedding six solenoids along the surface of a Nintendo Wii wheel, creating three bumps under each palm (Figure 3.1). In Study 2, the Cutaneous Push feedback was refined by relocating the push sensations on the palms, and tested under similar conditions as Study 1. These two studies focus on presenting *static* patterns to the driver's palms: all pins protrude simultaneously and retract simultaneously. In Study 3, *dynamic* patterns were investigated. Dynamic patterns include the animation of circular motion on the steering wheel by activating one pin after the other along the rim. The experiments in this chapter focus on perceivabiliy of Cutaneous Push patterns detached from any application such as gesturing or navigation.

3.1.1 Chapter Structure

Sections 3.2 and 3.3 describe the design of static Cutaneous Push feedback patterns on the steering wheel (Studies 1 & 2). Section 3.4 presents Study 3 which builds on the findings of the static patterns and introduces dynamic motion on the steering wheel. These three sections discuss the design of the Cutaneous Push feedback, methodology, and results, respectively. Section 3.5 discusses the limitations of the presented techniques and experiments; and gives conclusions and revisits the research question discussed earlier in this chapter.

3.2 Study 1: Cutaneous Push Feedback

3.2.1 Research Aims

The study presented in this section introduces *static* Cutaneous Push feedback on the steering wheel. The first aim of this study was to investigate the characteristics of an effective Cutaneous Push pattern. This includes the optimal number of simultaneously actuated solenoids, and the optimal interplay of actuated solenoids (i.e. presented unilaterally vs bilaterally, mirrored across both hands versus not mirrored).

Another aim was to investigate the physical setup of this feedback technique. This includes determining whether the locus of tactile feedback impacts usability. The solenoids deliver feedback to different locations on the palm, which may or may not affect their recognition. Further, the strength of the force feedback needs to be investigated since it may cause discomfort if it is too powerful or increase mental demand if it is too weak.

Finally, this study aimed at investigating the impact of Cutaneous Push feedback on driving performance as well as mental demand.

The three main aims of this experiment are to: (1) determine the characteristics of the most perceivable Cutaneous Push patterns; (2) the optimal physical setup; and (3) analyse which patterns impact driving performance and mental demand. These aims begin to contribute an answer to the first research question **RQ1**.

3.2.2 Methodology

Perception of Haptic Patterns Through the Palm

In order to design a Cutaneous Push feedback steering wheel for optimal message delivery to the driver, the tactile properties of the human hand need to be understood first, specifically the advantages of the palm. The most sensitive areas for Cutaneous Push feedback on the hand are the finger tips and the palm [19] (Figure 3.2, as discussed in Section 2.5.2). However, in a driving scenario, applying push force feedback to the finger tips might be dangerous to driver safety. Aldien *et al.* [202] have shown that to hold a cylindrical object, the palm pushes against it and the fingers grip it. This means that, if Cutaneous Push feedback is applied to the finger tips, the grip on the steering wheel might loosen which could result in a loss of control. To avoid the risk of endangering the driver, the choice was made to provide push feedback to the palm.

On the palm, primarily the thenar (thumb) region is receptive to pressure stimuli [19] (Figure 3.2). Aldien *et al.* [202] showed that for all subjects and cylindrical objects, there is definite contact between palmar region and the gripped object, not necessarily between the thumb region and the object. Thus, this study focuses on presenting push feedback from the steering wheel to the median palmar region to guarantee skin contact.

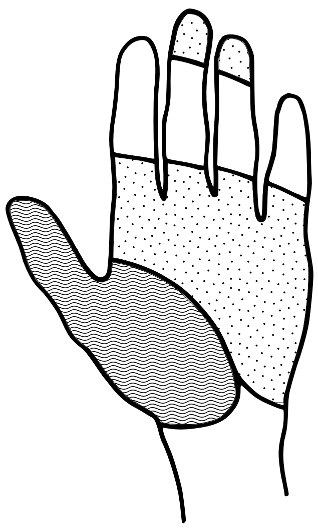


Figure 3.2: Inner left hand with its most sensitive regions to pressure input via a $1cm^2$ round metal pin. Wavy: thenar/thumb region; dotted: median palmar region is 10-20% less sensitive than thenar/thumb region; White: fingers are more than 20% less sensitive to pressure input than thenar/thumb region [19].

Push force as a medium of tactile feedback on the skin creates indentations. The range of optimal skin indentation on the palm to excite appropriate sensory units is between 2 - 5 mm [203]. When actuated, the pins creating the skin indentation should stick out 5 mm (0 mm when not). The pin states should be binary (up or down) to make the patterns as distinguishable as possible [204] since subtlety in haptic icons causes increased pattern discrimination errors [205]. The minimum threshold of perceivable pressure is 0.2 N [206, 207]. Given a pin of 1.75 mm, 3.2 N is the pain threshold [208].

The size of the push actuators and the size of the steering wheel constrained the potential number of solenoids to maximally three per side. Given six solenoids, with a binary state (in/out), 64 feedback patterns are possible. However, patterns with five or more active solenoids were taken out of consideration as a push feedback pattern as a result of the 'subitising' effect [209], resulting in 57 patterns to test. Subitising is the rapid, accurate, and confident judgments of numbers. Subitising is fast and nearly errorless for up to 4 stimuli. But if more than 4 stimuli are presented, counting starts which is slow and errorprone [209]. The motivation behind the presentation of a maximum of four stimuli at the same time is that the feedback should not introduce additional mental effort (i.e. counting) to the already demanding task of driving.

Figure 3.3: OpenDS 3's five lane motorway.

Feedback Design

Six solenoids are embedded into the steering wheel, three on each side of the rim (Figure 3.1) so that they create "bumps" in the median palmar region on each hand (Figure 3.2). The solenoid pins were covered by a latex sheet to enlarge the contact surface with the hands and reduce "stabbiness" of the protruding metal pins. The solenoids can be moved in and out individually which results in 64 possible patterns (in/out^2). However, maximally four [209, 210] of the six solenoids were actuated simultaneously, resulting in 57 patterns to test.

Apparatus

According to Fransson and Winkel [211], 79mm and 90mm are the average hand breadths for females and males respectively. The physical layout of the solenoids allowed a minimum distance of 17.6 mm from pin to pin. To ensure perception by both genders, a maximum of three pins per palm could be implemented. The solenoid pins in this setup were 1.5 mm wide and they reached a maximum of 2.9 N (DC) at 100% duty cycle. The prototype haptic steering wheel was securely attached on top of a Logitech G27 racing wheel [212] so that participants could steer the virtual vehicle during a simulated driving task (OpenDS 3 [213]). The prototype wheel was a Nintendo Wii steering wheel [214] of 19 cm diameter (a real world car steering wheel diameter is 38 cm [215]. The Cutaneous Push interface was implemented into a Wii steering wheel to pilot test its feasibility and efficacy. Thus, the decision to opt for a solution which was low in cost and time consumption was reached. The nomenclature of the pins is as follows (Figure 3.4): top left pin is L1, middle left pin is L2, bottom left pin is L3. This is the same for the right hand pins.

OpenDS is an open source driving simulator built in Java (Figure 3.3). It comes with pack-

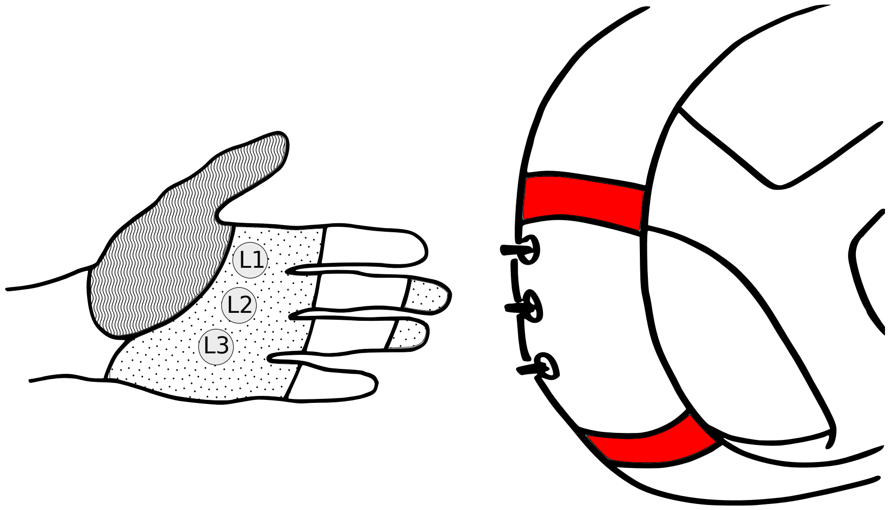


Figure 3.4: (a) Inner left hand (Figure 3.2). The dots indicate which location to which the solenoids provided feedback. (b) Steering wheel with three extruding Cutaneous Push pins. Red markers indicate where the participants' hand was placed.

ages such as lane change task and vehicle platooning tasks. It is an easily extendable platform used in the automotive driving research community [216].

The experiment was conducted in a usability laboratory equipped with 1) a computer, on which the OpenDS Version 3 simulation was run, 2) a 27 inch monitor to display the driving simulation, 3) six solenoid powered pins protruding from the steering wheel providing feedback to the driver's palms [20], 4) Phillips SBC-HP 200 headphones, and 5) a mouse and keyboard were provided for the participants to give feedback. The headphones were used to mask out the noise produced by the solenoids; car engine sound from the driving simulator was presented to the driver.

Measures

The Independent Variable was: haptic pattern. The Dependent Variables were: primary task performance (latitudinal lane deviation, i.e. metres from centre of lane), secondary task performance (pattern recognition accuracy if *all* the pins for each pattern were selected correctly; otherwise, the trial was counted as incorrect, subjective effort (Likert scale), and questionnaire.

Pattern Design

Two of the three aims of this study are to a) determine the characteristics of the most perceivable Cutaneous Push patterns and b) the optimal physical setup. The following parameters allow for an investigation into these two aims:

Number of active pins per pattern can provide an insight into recognition accuracy depending on stimuli count. Zero up to four pins will be actuated simultaneously. Zero pins being active was one possible pattern. The purpose of this pattern was to determine whether participants felt phantom tactile sensations when there was no haptic feedback.

Locus of pin presentation was determined by whether the pin was presented to the top median palmar region below index finger (L1, R1), the middle median palmar region (L2, R2), or the lower median palmar region (L3, R3) (Figure 3.4). **Adjacent** presentation concerns whether the pins are next to each other (e.g. L1-L1, R2-R3).

Ipsilateral presentation means patterns were presented to one hand only. **Bilateral** presentation describes a pattern presented to both hands. This can be either a *mirrored* or an *unmirrored* pattern. Mirrored patterns are defined as the same stimuli occurring on both hands (e.g. L1-R1, or L1-L3-R1-R3). *Unmirrored* patterns take place on both hands also, but not the same stimuli are fired (e.g. L2-L3-R2, or L1-R2).

Hypotheses

- **H1** Perception accuracy of patterns drops with a) increasing number of active pins per pattern, b) immediate adjacency of pins, c) ipsilateral Cutaneous Push presentation rather than bilateral, d) locus of stimulus;
- **H2** Cutaneous Push patterns will not impact driving negatively;
- **H3** Cutaneous Push patterns do not effect subjective effort negatively.

H1.a anticipates an increase in erroneous judgements regarding the number of actuated pins. Research has shown that the more tactile stimuli are presented simultaneously, the higher the chance of falsely judging active tactors [210]. This is firstly due to the masking effect, in which one stimulus affects the detection of another. The masking effect increases as the number of stimuli increase [217, 218]. However, research [219] has shown that masking is more prevalent if presented ipsilaterally (on one hand) than bilateral (across both hands) because of the phenomenon of "apparent location" which might influence perception performance. This phenomenon describes the summation of two tactile stimuli on the skin to one if they are presented simultaneously [220]. Therefore, hypothesis **H1.b** expects a decrease in perception accuracy if the pins are adjacent to each other. This ties into hypothesis **H1.c** which consequently expects better perception accuracy if the patterns are presented bilaterally.

H1.d expects a drop in perception from L1 and R1 towards L3 and R3. Fransson and Hall showed [19] that primarily the thenar (thumb) region is receptive to pressure stimuli; this suggests, the closer the Cutaneous Push feedback is presented to the thumb region, the higher its perception.

H2 states that the presentation of Cutaneous Push feedback will not impact driving performance negatively. The following two factors predict no loss in steering control over the car: a) the protrusion strength of the solenoids is below the pain threshold and thus will not cause any discomfort and thus loosened grip; b) Cutaneous Push feedback is presented to the palm and not the fingers, which does not impact the gripping action on the steering wheel.

H3 does not predict significant increase in subjective effort of classifying the Cutaneous Push patterns. According to Gallace *et al.* [210], the subitising effect, which is fast and nearly errorless for up to 4 stimuli, stops and active counting starts. During this study, maximally four tactile stimuli will be presented at any given time.

Procedure

A simulated driving task was used to measure the efficacy of Cutaneous Push feedback from the steering wheel. A within-subjects design was chosen. Participants were driving in the centre of a 5 lane motorway without any other road users nor any maneouvering instructions. This design was chosen for easy measurement of potential effects of the Cutaneous Push feedback.

The tactile patterns were presented on the steering wheel which the participant was asked to hold throughout the experiment. During the experiment, the randomly ordered 57 patterns were presented twice to each participant. There was one experimental condition with varying tactile patterns (the number and permutation of actuated solenoids). The tested patterns are listed in Table 3.1.

In each trial (Figure 3.5), the participant drove on the simulated motorway holding the steering wheel and awaited the cued stimulus (8-12 seconds). This interval of driving prior to pattern presentation is classified as *before* pattern presentation. Cutaneous Push feedback was presented for 3 seconds (as a result of max. 4 solenoids and 500-800 ms to shift attention [19]). This interval is labelled as *during* pattern presentation. Another 3 seconds *after* stimulus display were required to allow the participant to return to stabilised driving. The duration for *before* and *after* pattern presentation intervals resulted from a pilot study. It showed that participants required 4 seconds to return to stabilised driving prior to haptic pattern presentation and 3 seconds post-presentation. Finally, during the feedback interval, the simulation was paused and a pop-up box appeared on the screen (Figure 3.6). Participants indicated what pattern was felt by checking the check box next to its associated actuator on the feedback screen. Seven blocks with each 15 patterns were tested. Participants rested between blocks.

At the end of the study, participants provided feedback about the entire system on a Likert scale: whether it was pleasant, distracting, useful and if they felt they were given enough

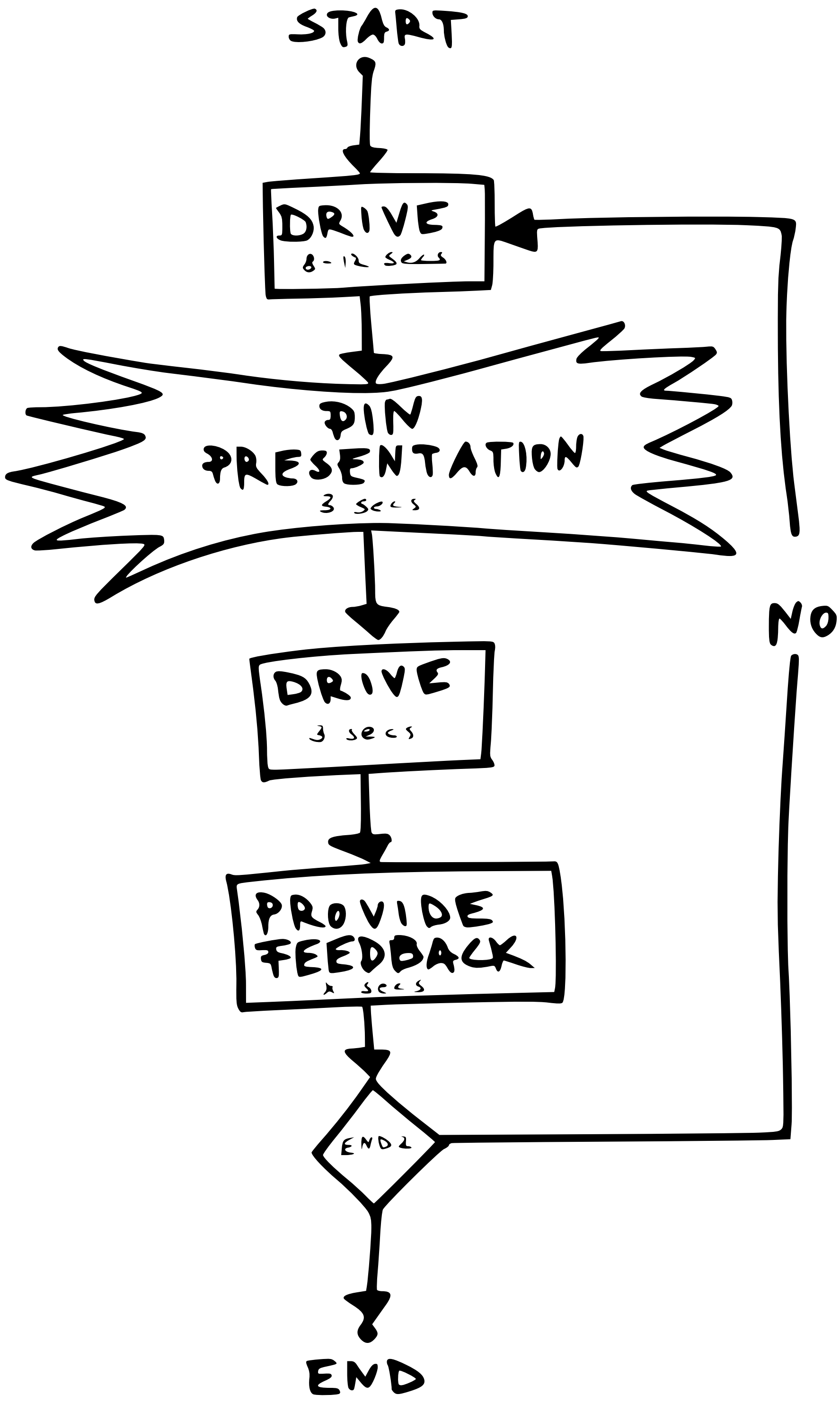


Figure 3.5: Flow chart of a single trial. A single trial consists of: participant drives for 8-12 seconds straight, a pin is presented for 3 seconds, the participant continues driving straight for another 3 seconds, and then is asked to provide feedback on what they perceived. If it happened to be last trial during the block, the simulation ends; otherwise the next trial starts in the same fashion as explained above.

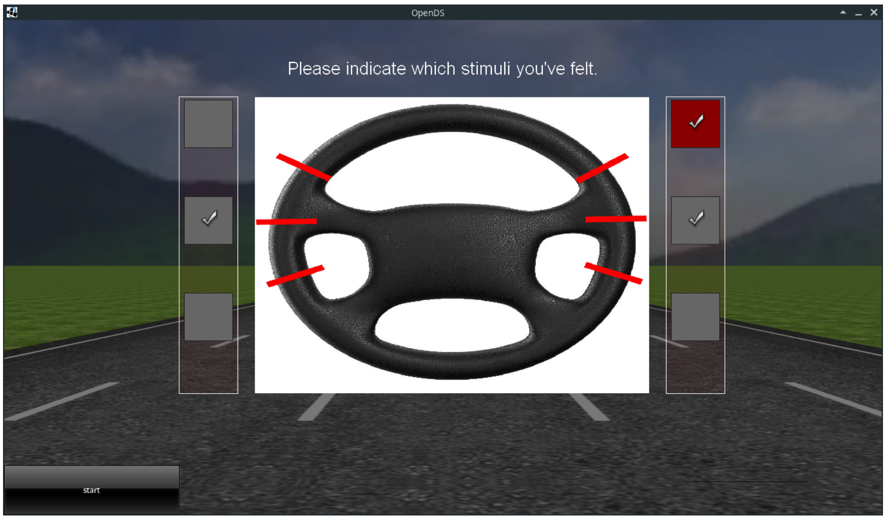


Figure 3.6: Screen for feedback input. Participants used the mouse provided to tick a box next to a pin to indicate which one(s) they perceived.

time to perceive the patterns. Finally, participants discussed characteristics of the perceived patterns.

Participants

Twenty participants (10 female) aged between 18 and 32 years (μ=23.0, σ=3.6) were recruited via the University of Glasgow's student online forum. Of these 20, 11 participants obtained their driving license in a country with Left-Hand-Traffic (LHT) and 9 a Right-Hand-Traffic (RHT) license. None of the participants took part in the previous studies on Cutaneous Push feedback. Two participants reported to be left handed. They were paid £10 at the end of the study.

3.2.3 Results

Recognition Performance

The accuracy data were binary since the participants either correctly or incorrectly identified the presented pattern. Table 3.1 shows which patterns were identified correctly on average showing the mean accuracy (%) for each pattern. Patterns with one (88%) or two (68%) pins were perceived most accurately. The more pins were involved in a pattern the less accurate was the identification, with three pins with 48% and four with 36% recognition accuracy.

The overall accuracy of identifying the correct pattern is 60.2%. The participants perceived zero pins with 96.7% accuracy. Taking out the patterns consisting of four pins increased

Pins per pattern	0	1	2	3	4
Recognition accuracy	96.7%	82.2%	78.1%	68.2%	60.2%

Table 3.1: Perception of patterns given the number of active pins (averaged). With increasing number of active pins per pattern, the recognition accuracy decreased.

L1	L2	L3	R1	R2	R3
91.16%	84.34%	86.08%	89.32%	87.31%	89.88%

Table 3.2: Individual perception of the pins averaged over all participants.

the overall accuracy from 60.2% to 68.2% (Table 3.1). Taking out three pin patterns further increases overall accuracy from 68.2% to 78.1% (Table 3.1). A logistic regression was performed to ascertain the effects of number of actuated pins on the likelihood that participants recognised the pattern correctly. The logistic regression model was statistically significant, $\chi^2(5) = 27.402, p < .0005$. A binomial regression with Tukey *posthoc* test revealed that the number of presented pins influences the performance significantly ($\chi^2(4, N = 2271) = 329.196, p < 0.0001$) (Tables 3.1).

To determine which pin affected accuracy the most, a Friedman test was conducted. There was a significant difference between the perception of the individual pins ($\chi^2(1, N = 2271) = 261.347, p < 0.0005$). Chi-square tests revealed the percentages of accuracy for each pin individually (Table 3.2).

The combination of active pins (i.e. the patterns) had a different influence in overall performance. A Chi-square test was calculated comparing the error rates of mirrored and un-mirrored patterns. A significant interaction was found ($\chi^2(1, N = 1674) = 60.784, p < 0.0005$) with 66.4% of presented mirrored patterns resulting in correct identification, compared to 53.0% of un-mirrored patterns. Due to the design, mirrored patterns included two and four pin patterns only. 68% of the un-mirrored two pin patterns were correctly identified, whereas 78.3% of the mirrored two pin patterns were correctly identified ($\chi^2(1, N = 599) = 4.305, p < 0.023$). 29.1% of not mirrored four pin patterns resulted in correct identification, and 43.3% of the mirrored four pin patterns ($\chi^2(1, N = 597) = 8.877, p < 0.002$).

Binomial regression showed that ipsilaterally presented Cutaneous Push patterns resulted in lower recognition (63.68%) than bilaterally presented patterns (70.87%) ($z = 3.046, p < 0.002$). Only two pin patterns were tested; either two pins adjacent on one hand, or one pin presented to each hand. Binomial regression on whether adjacency of pins influences pattern perception accuracy showed significance ($z = 3.565, p < 0.001$). Adjacent pins had a 44.67% accuracy rate, whereas non-adjacent pins had 68.97% accuracy.

A repeated measures analysis of variance (ANOVA) revealed that the locus of the Cutaneous Push feedback has a significant impact on recognition rate ($\chi^2(1, 6) = 17.015, p < 0.001$). A A one-way multivariate analysis of variance (MANOVA) test revealed that the L2, L3, R1, and R3 pins influenced the rate of recognition success with $F(40, 1) = 11.043, p = 0.002$, $F(40, 1) = 15.276, p < 0.001$, $F(40, 1) = 14.073, p < 0.001$, and $F(40, 1) = 26.682, p < 0.001$ respectively (Table 3.2).

Driving Performance

Driving performance was measured via deviation from the optimal driving path; the more deviation from the optimal path, the worse the driving performance. In this study, the centre of the middle lane was considered as zero lane deviation, i.e. the optimal driving path. As exemplified in previous research [221], vehicle lane deviation was measured through the root mean square error (RMSE) of its lane position with respect to the lane centre. This resulted in a non-normal distribution of driving data for *before* ($W = 0.871, p <= 0.001$), *during* ($W = 0.847, p <= 0.001$), and *after* ($W = 0.857, p <= 0.001$) driving intervals — as shown by Shapiro-Wilk normality tests.

The presented pattern had no significant impact ($chi^2(1) = 0.031, p = 0.861$) on driving behaviour. However, a MANOVA test revealed that pattern recognition success had a significant impact on lane deviation ($chi^2(1) = 6.293, p = 0.012$) *before* pattern presentation; the success of correctly recognising the pattern had no impact on driving deviation neither *during* ($chi^2(1) = 2.29, p = 0.076$) nor *after* ($chi^2(1) =, p = 0.557$) pattern presentation.

Qualitative Data

In the questionnaire, participants were asked to rate whether the Cutaneous Push patterns were pleasant, distracting, and useful (Table 3.7) on a scale from 1 to 5 with 5 being "agree strongly"; as well as if they were given enough time to perceive the patterns. Participants were neutral about the feedback's usefulness (11/20) and its pleasantness (9/20). They generally disagreed with the patterns being distracting (10/20).

Characteristics of easily perceivable patterns emerged (open-ended questionnaire data in Appendix A). Participants thought Cutaneous Push patterns were easily perceivable if: a) the stimuli were not adjacent to each other (19/20 participants); b) only one or two pins were actuated (10/20); c) if patterns were presented ipsilaterally, then presentation of all pins supported perception (5/20); and d) if patterns were presented bilaterally, then mirroring the pattern supported perception (6/20). Participants thought Cutaneous Push patterns were harder to distinguish if: a) middle (4/20) and b) bottom (8/20) pins were presented; c) if they were presented bilaterally (5/20); and d) if they were presented ipsilaterally (6/20). Finally, the top pins (L1 and R1) were perceived as most attention grabbing (6/20).

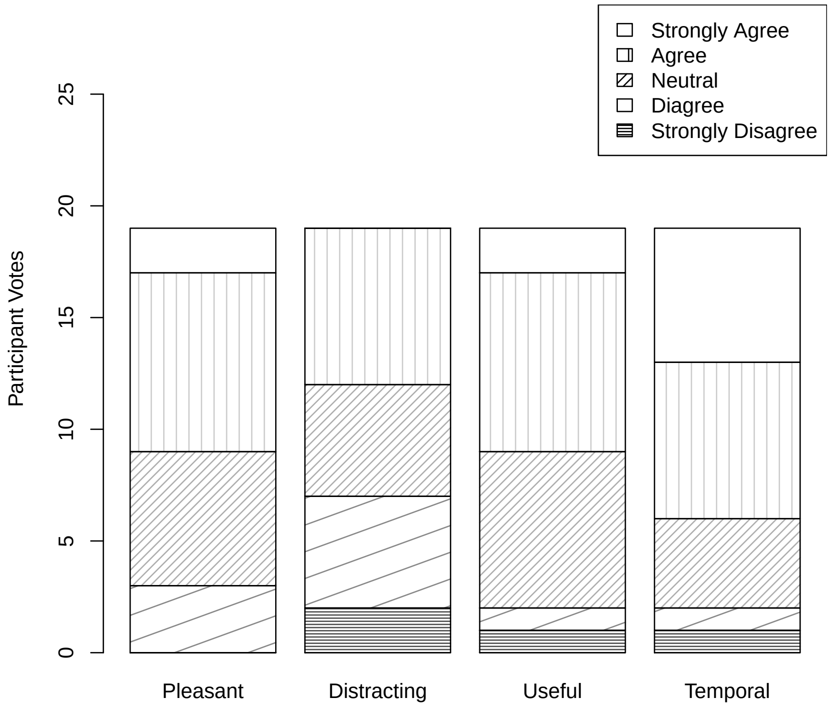


Figure 3.7: Questionnaire results. Participants were asked whether the Cutaneous Push patterns were pleasant, distracting, useful, and if they were given enough time to perceive the patterns.

3.2.4 Discussion

Study 1 was an initial investigation into Cutaneous Push feedback on the steering wheel. The technology illustrated in this section allowed the user to perceive 57 different Cutaneous Push stimuli via three solenoids embedded into the steering wheel under each palm. The results have shown that participants recognise Cutaneous Push messages with 78.1% accuracy if a maximum of two pins are used. Patterns consisting of four pins caused low recognition performance (60.2%).

> **H1** Perception accuracy of patterns drops with a) increasing number of active pins per pattern, b) immediate adjacency of pins, c) ipsilateral Cutaneous Push presentation rather than bilateral, d) locus of stimulus

Thus, the number of actuated solenoids influences the pattern identification rate significantly, supporting **H1.a**. This is in accordance with the findings made by Gallace *et al.* [210] where it was suggested to limit the number of tactile actuators to maximally four. Participants mentioned a difficulty to localise adjacent pins correctly. This is in accordance with the quantitative findings: adjacent pin patterns had a significantly worse identification rate 44.67% than non-adjacent pin patterns 68.97%, supporting **H1.b**. The results suggest that Cutaneous Push stimuli which are situated next to each other decrease perception accuracy and can increase perceived effort to distinguish the pattern.

H1.c anticipated higher recognition for bilateral patterns than ipsilateral patterns due to the "apparent location" phenomenon, suggesting masking is more prevalent if two tactile stimuli on the skin are close to each other, resulting in a summation of both [220]. Ipsilaterally presented two pin patterns had a recognition average of 63.68% and bilaterally presented two pin patterns had an average of 70.87%. Hypothesis **H1.c** was accepted; Cutaneous Push patterns result in better perception performance if they are presented to both hands rather than one.

Participants noted in the questionnaire that"asynchronous patterns" (P19) presented to both hands caused increased efforts to distinguish; that is *unmirrored* patterns. Analysis showed, that patterns which are presented bilaterally benefit from mirroring; that means, same stimuli are activated across both hands such as L1-R1 or L2-L3-R2-R3. *Mirroring* bilaterally presented Cutaneous Push patterns increased perception accuracy because information was displayed redundantly to both hands, confirming the pattern; mirroring supported and increased pattern recognition from 50.8% (unmirrored) to 66.4% (mirrored).

Finally, the most perceivable pins were L1 and R1 with 91.16% and 89.32%, which is supported via participants' feedback. Hypothesis **H1.d** was accepted. Analysis shows that pins L3 and R3 caused significantly more identification errors on each hand than the other pins;

8/20 participants reported poor perception from L3 and R3 pins. These results show, that the locus of Cutaneous Push stimuli impacts recognition accuracy; pins presented closer to the thumb area had a greater perception success.

H2 Cutaneous Push patterns presentation will not impact driving negatively

Hypothesis **H2** was accepted since the presentation of Cutaneous Push feedback did not impact driving performance. Interestingly, success rate of recognition impacted driving behaviour *before* pattern recognition. In the *before* interval, participants recovered to stabilised driving after the feedback pause. A possible explanation to why the *before* interval may have impacted pattern recognition success is that the *before* duration might not have been sufficiently long enough for participants to recover from the feedback-break. The participants were preoccupied with returning to stabilised driving (as the results show), thus they prioritised driving over Cutaneous Push pattern perception.

H3 Cutaneous Push patterns do not impact subjective effort negatively.

Finally, hypothesis **H3** was accepted since 12/20 participants (strongly) disagreed that the Cutaneous Push technology was distracting and 15/20 (strongly) agreed that they did not feel temporal pressure to complete the task.

3.2.5 Limitations

The Cutaneous Push feedback steering wheel used in Study 1 was a prototype device, and a key aim of this study was a first estimate of the perception of the feedback patterns. Analysis of the data and user feedback showed study limitations which can be improved upon. For instance, participants thought the pins were not “forceful” (P9) or “sharp” (P13) enough and that the Cutaneous Push feedback patterns should “be more obvious” (P1). Noticability of Cutaneous Push feedback can potentially be increased with stronger solenoids. However, to avoid pain, the solenoid pins utilised in this study only created 2.9 N (DC) at 100% duty cycle. This limitation can be mitigated by embedding stronger solenoids into the rim. The steering wheel was also covered in a latex sheet to increase contact surface with the solenoids, but this might have decreased the strength of their impact. Participant P6 suggested additionally that the contact between the solenoids and the palm can be optimised with the use of “little plastic balls [..] on the tip” instead of a cover. The motivation behind the usage of a latex sheet was partially influenced by the fact that they may increase contact surface with the palm. Instead of a single point of contact, there was a convoluted surface. However, this might have caused additional blurring of the location of the pin by enlarging the contact surface.

Another issue was mentioned by participant P8 "[I] would separate the actuators a bit more for larger hands" and P15 supported the view with "probably use a larger steering wheel and have slightly stronger solenoids". A greater distance between the stimuli was also suggested by participants P10 ("larger actuators or more spread apart") and P12 ("[the solenoids] could be a little bit more spaced out"). The mock steering wheel in this study was 19 cm in diameter (compared to real steering wheels with 38 cm diameter) and attached on top of a gaming steering wheel. A large steering wheel may allow for a larger distance between the pins, which can decrease the phenomenon of summation of two stimuli. The feedback from participants suggests that a larger steering wheel may improve pattern perception performance.

To summarise the user feedback, the next generation of the Cutaneous Push steering wheel should implement: a) stronger solenoids, b) plastic domes on the tips of the solenoids instead of a latex cover, and c) increase the space between the solenoids.

Two issues in the study design will be improved upon in the next iteration. Firstly, the design of the Cutaneous Push steering wheel did not present feedback to the thumb region, which is associated as most sensitivity to pressure input [19]. If stimuli are presented to the thumb instead of the bottom of the palmar region (e.g. L3 and R3), perception may improve. Finally, the perceived demand was not measured via a NASA TLX score, thus no conclusive results could be drawn. This will be remedied in future experiments.

3.2.6 Summary

The three main aims of this experiment were to: (1) determine the characteristics of the most perceivable Cutaneous Push patterns; (2) the optimal physical setup; and (3) analysis of which patterns impact driving performance and mental demand. These aims began to contribute an answer to the first research question of this thesis:

> **RQ1:** How effective is Cutaneous Push feedback from the steering wheel to the driver's palm (*Studies 1, 2, & 3*)?

Of the three hypotheses identified in Section 3.2.2, all were accepted. This study shows that Cutaneous Push patterns, which are constructed using three pins on each hand, can be conveyed to the user with high accuracy, if maximally two pins are actuated simultaneously. Cutaneous Push feedback does not impact driving performance and might not impact perceived efforts. However, this study also revealed room for improvements in following points:

1. The strength of the solenoids should increase because participants described them as too weak;

2. The solenoids should not be covered by any film since it dampens the impact of the feedback;

3. The steering wheel size needs to increase to allow for greater distances between the pins to reduce the summation of tactile stimuli;

4. Loci of stimuli need to be improved such as that feedback can be presented to the thumb;they can provide feedback to the most appropriate areas on the palm.

3.3 Study 2: Refined Cutaneous Push Feedback

A new steering wheel design was created informed by the results of Study 1 and suggestions by participants. Four changes were made. Firstly, rather than using a Wii gaming steering wheel (19 cm in diameter) attached on top of a Logitech steering wheel, a 38 cm metal steering wheel was obtained (Figure 3.8) and secured to the base of the steering wheel system. The new steering wheel was the same size as a production car steering wheel, thus more realistic for purposes of hand placement.

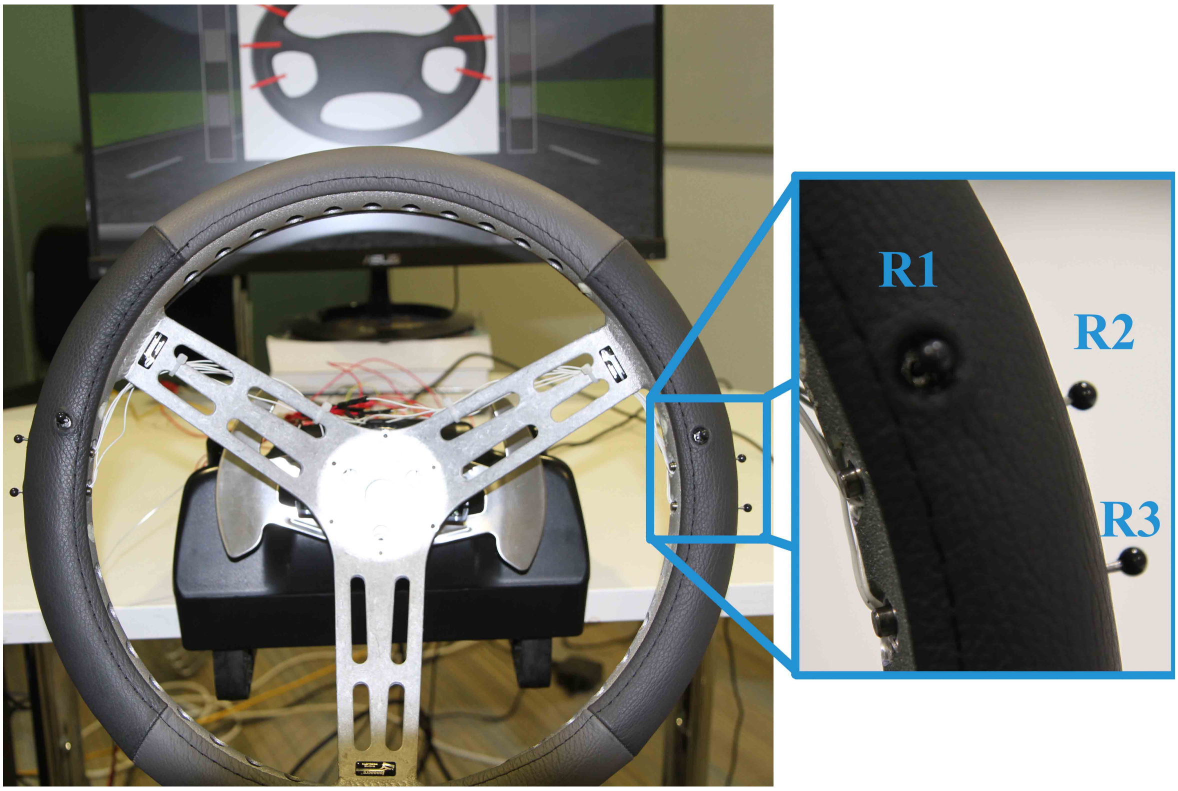


Figure 3.8: Left: The new steering wheel with six solenoids embedded into the rim (three on each side). Right: Close-up of the activated pins on the right side.

Secondly, the choice to purchase a larger steering wheel made a redesign of the Cutaneous Push feedback locations possible (Figure 3.9). The solenoids in the new design were placed such that feedback was presented to the thenar/thumb region through L1 and R1; and feedback to the bottom median palmar region was omitted. This design choice resulted from the poor perception of the L3 and R3 pins in Study 1. The choice to redesign feedback locations was also supported by the fact that feedback could now be presented to the thenar/thumb region, the most sensitive region for pressure on the palm. The distance between stimulus loci further enlarged from 17.6 mm in Study 1 to 30 mm. The choice to place the solenoids exactly 30 mm apart form each other was made because in the first study persons with hand breadths of ˜70 mm participated; a 30 mm distance between pins allows people with small hands to successfully cover the pins with their palms and perceive the Cutaneous Push feedback.

Thirdly, in this design, the pins were covered with plastic domes to soften the “stabbiness” of the metal pins, rather than a latex sheet. This decision was made because the latex sheet dampened the impact of the pins and may have caused a blurring of the location of the pin by enlarging contact surface in Study 1. Finally, stronger solenoids [222] were embedded into the rim due to participant’s feedback that they were perceived as too weak in Study 1. The strength of the new solenoids is 4.18 N, compared to 2.9 N in the previous study. The new strength was determined during pilot tests, with the aim to keep it below 5N. Research has shown that elongated exposure to pressures of $>=$ 5N to the palm can decrease blood flow to the fingers [223].

To summarise, the main differences between Study 1 and Study 2: (1) presentation of haptic feedback to thenar and median palmar region compared to palmar region only, (2) stronger solenoids (4.18 N vs 2.9 N), (3) an alternative method for dampening the impact of the haptic feedback, and (4) size of the steering wheel (38.1 cm vs 19 cm diameter). The changes in design were made to increase perception accuracy of the Cutaneous Push feedback.

3.3.1 Research Aims

Due to the redesign of the steering wheel it was necessary to conduct a study to investigate the efficacy of the new Cutaneous Push wheel, before employing this technique for mid-air gesture interaction. Similarly to Study 1, the first aim was to investigate the characteristics of an effective Cutaneous Push pattern, meaning the optimal interplay of actuated solenoids (i.e. presented unilaterally vs bilaterally, mirrored across both hands vs not mirrored, etc).

The second aim was to investigate the physical setup. The aim was to determine whether the new locus of tactile feedback impacted usability by affecting recognition. Further, the strength of the force feedback needed to be investigated since it may cause discomfort if it is too powerful or increase mental demand if it is still too weak.

Finally, this study investigated the impact of Cutaneous Push feedback on driving perfor-

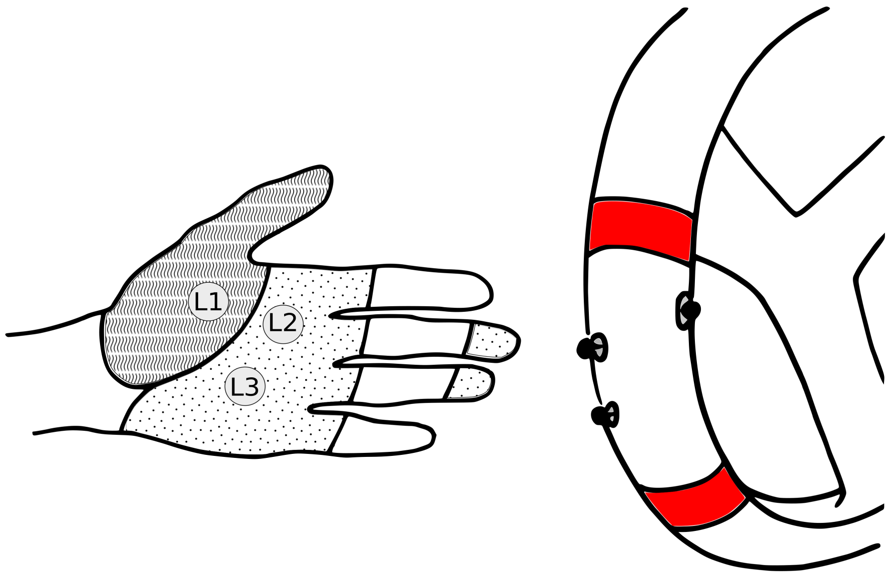


Figure 3.9: (a) Inner left hand with its most sensitive regions to pressure input via a $1cm^2$ round metal pin. Wavy: thenar/thumb region; dotted: median palmar region is 10-20% less sensitive than thenar/thumb region; White: fingers are more than 20% less sensitive to pressure input than thenar/thumb region [19]. The dots indicate where the solenoids were placed. (b) Steering wheel with three extruding Cutaneous Push pins. Red markers on the wheel indicate where the participants' hand was placed.

mance as well as perceived demand. It is important to understand whether solenoid feedback impacts driving performance or workload to ensure driver safety.

The three main aims of this experiment are to: (1) determine the characteristics of the most perceivable Cutaneous Push patterns; (2) the optimal physical setup; and (3) analyse which patterns impact driving performance and perceived demand. These aims help to contribute an answer to the first research question of this thesis:

> **RQ1:** How effective is Cutaneous Push feedback from the steering wheel to the driver's palm (*Studies 1, 2, & 3*)?

3.3.2 Methodology

The study design is the same as in Study 1 (Section 3.2.2) unless it is explicitly stated that there is a difference (i.e. sections Apparatus, Measures, Procedure, and Participants).

Apparatus

Six solenoids [222] were embedded into a pre-drilled metal steering wheel [215] (Figure 3.10). The solenoids were labelled according to the side of the wheel they were on and

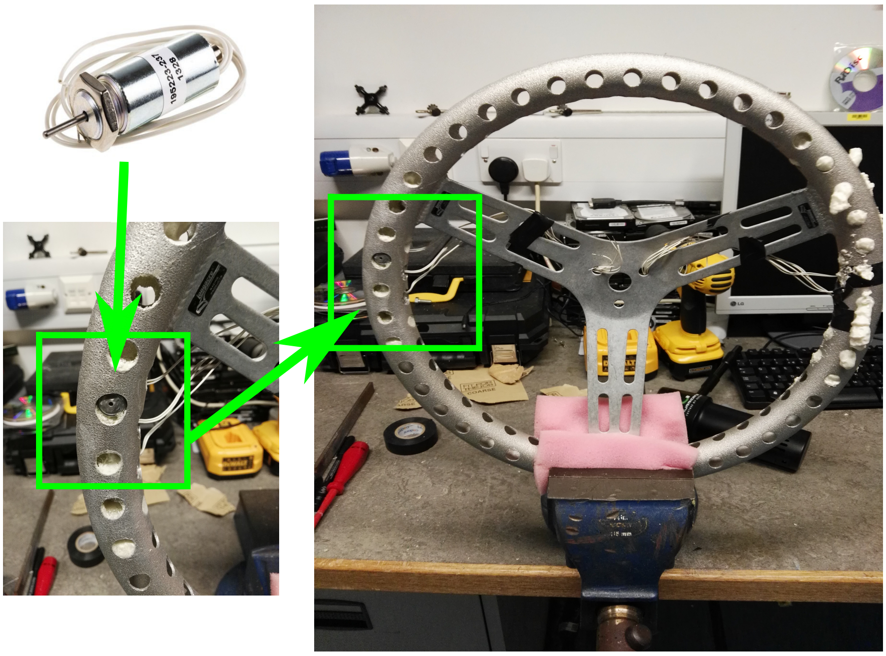


Figure 3.10: The pre-drilled long acre racing wheel. Six solenoids were placed inside it, and the steering wheel was filled with foam to maintain the solenoids' positions (see right). The steering wheel was finally covered in a standard leather steering wheel cover (Figure 3.8)

numbered from top to bottom: L1/R1 (top left/right), L2/R2 (middle left/right) and L3/R3 (bottom left/right), see Figure 3.8. Two solenoid pins (R2/R3 and L2/L3) provided feedback to the median palmar region, and one solenoid pin (R1 and L1) provided feedback to the thenar/thumb region (Figure 3.8). R2-R3 and L2-L3 are 30 mm apart from each other (17.6 mm in Study 1), and all the pins extend 5 mm. The solenoids exerted a force of up to 4.18 N. Plastic domes (diameter of 0.4 cm) were mounted on the solenoid pins to increase contact area and avoid pain on contact. The steering wheel was securely attached to a Logitech G27 Racing Wheel base, replacing the original steering wheel (Figure 3.1). The driving simulator is the same as in Study 1 and it was setup the same (i.e. five lane motorway, etc).

Measures

The Dependent Variable *perceived workload* was assessed using the NASA TLX workload measure.

Hypotheses

H1 Perception accuracy of patterns drops with a) increasing number of active pins per pattern, b) immediate adjacency of pins, c) ipsilateral Cutaneous Push presentation rather than bilateral, d) locus of stimulus, e) unmirrored patterns bilateral patterns

Figure 3.11: Left: Extended solenoid pin. Right: Retracted solenoid.

Hypothesis **H1** was amended compared to Study 1's **H1**: point e) was added. As the results of the previous experiment showed, mirrored patterns resulted in higher pattern recognition than unmirrored ones.

Procedure

At the end of the experiment, perceived workload was assessed using the NASA TLX questionnaire.

Participants

Nineteen participants (7 female) aged between 19 and 66 years (μ=27.8, σ=10.3) were recruited via the University of Glasgow's student online forum. Of these 19, twelve participants obtained their driving license in a country with Left-Hand-Traffic (LHT) and seven a Right-Hand-Traffic (RHT) license. None of the participants took part in either of the previous studies on Cutaneous Push feedback. Three participants reported to be left handed. They were paid £10 at the end of the study.

3.3.3 Results

Recognition Performance

The accuracy data was binary since the participants either correctly or incorrectly identified the presented pattern. Average Cutaneous Push pattern recognition accuracy was 77.35%.

Pins per pattern	1	2	3	4
Recognition accuracy	89%	80.43%	72.6%	65.1%

Table 3.3: Perception of patterns given the number of active pins (averaged). With increasing number of active pins per pattern recognition accuracy dropped.

Patterns with one (89%) or two (80.43%) pins were perceived most accurately. The more pins were involved in a pattern the less accurate was the identification, with three pins with 72.6% and four with 65.1% recognition rates. A binomial regression was run to determine whether the number of pins per pattern had an impact on recognition rate. The more pins were displayed per feedback, the worse the identification ($z = 8.993, p < 0.001$). A MANOVA test revealed that the L2, L3, and R3 pins influenced rate of recognition success with $F(40, 1) = 8, p = 0.007$, $F(40, 1) = 8.342, p = 0.006$, and $F(40, 1) = 9.703, p = 0.003$ respectively. The pins have following average success rates: L1 96.52%, L2 94.51%, L3 90.20%, R1 97.03%, R2 95.29%, and R3 94.24%.

A binomial regression model was fit to predict whether presentation of patterns ipsilaterally or bilaterally had an impact on recognition performance. There is a statistically significant impact of correct pattern identification ($z = 5.900, p < 0.001$) if presented to one hand 79.24% over both hands 80.83%.

A binomial regression model was fit to predict whether mirroring a pattern across both hands had an impact on correct pattern recognition. There is a statistically significant impact ($z = 6.024, p < 0.001$) with mirrored patterns resulting in 79.34% correct identification and non-mirrored patterns in 76.85%.

A binomial regression model showed there is a significant difference in pattern recognition depending on adjacency of pins ($z = 7.176, p < 0.001$). If pins in a pattern are next to each other, 71.92% of patterns are correctly identified; if pins are not adjacent to each other, 81.79% are correctly identified.

Driving Performance

Driving data was non-normally distributed for *before* ($W = 0.712, p - value < 0.001$), *during* ($W = 0.681, p <= 0.001$), and *after* ($W = 0.668, p <= 0.001$) driving intervals — as shown by Shapiro-Wilk normality tests. Four of 19 participants deviated to an outer lane immediately after commencing the experiment and stayed there for the remainder of the time. These data were normalised by subtracting the mean of the lane the participants deviated to from the raw data (middle lane $\mu = 0$ m, inner lanes $\mu = \pm 3.7$ m, outer lane $\mu = \pm 7.4$ m).

A one-way multivariate analysis of variance (MANOVA) was conducted to test the hypothesis that there would be one or more mean differences between presented pattern and success in recognising the pattern. No statistically significant MANOVA effect was obtained for recognition accuracy before *before* ($F(3,38) = 0.097, p = 0.756$), *during* ($F(3,38) = 0.055, p = 0.814$), and *after* ($F(3,38) = 0.008, p = 0.926$) haptic pattern presentation; it did not show any impact of presented pattern on lane deviation (*before* $F(1,1386) = 3.383, p = 0.066$; *during* $F(1,1386) = 1.749, p = 0.186$; *after* $F(1,1386) = 0.664, p = 0.415$).

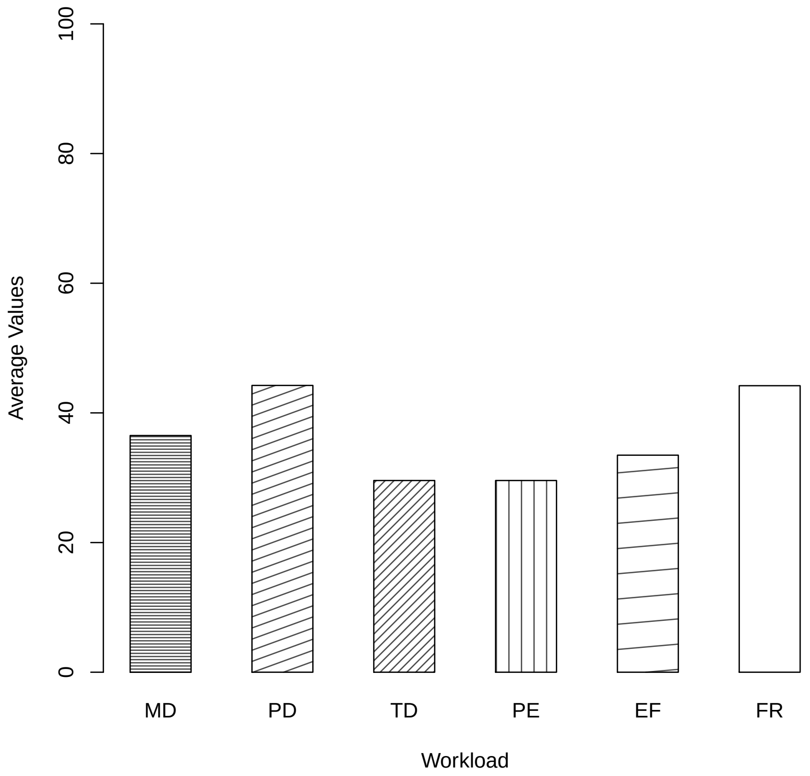


Figure 3.12: Average results of the NASA TLX questionnaire. MD: Mental Demand, PD: Physical Demand, TD: Temporal Demand, PE: Performance, EF: Effort, FR: Frustration.

Qualitative Data

Users provided mental workload feedback via NASA TLX score (Figure 3.12), and responded to open-ended questionnaire questions. User preferences regarding the position of the pins were as follows: 10/19 preferred R1/L1 over the other pins, 7/19 liked the R2/L2, and 2/19 mentioned R3/L3 to be most preferred. 10/19 participants reported that it was hard to distinguish between the median palmar pins R2/R3 or L2/L3. The least distracting pins were considered to be L1 and R1 with 6/19. Furthermore, symmetrically mirrored patterns (5/19), ipsilateral patterns (5/19), and single stimulus patterns (4/19) were considered to be the least distracting. Other participants did not have any strong preferences. The most distracting patterns were unmirrored patterns (4/19) and patterns presented to the median palm

(L2-L3, R2-R3) (5/19). Haptic patterns with less than three active solenoids were rated as less distracting by 16/19 participants.

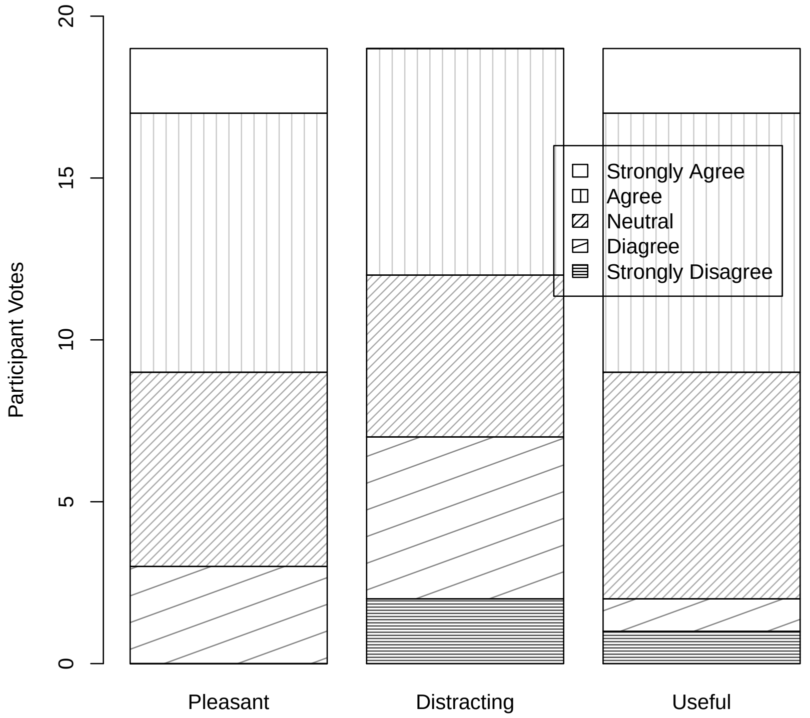


Figure 3.13: User feedback on how pleasant, distracting, useful Cutaneous Push feedback is perceived. Temporal indicates whether participants felt they were given enough pattern display time.

3.3.4 Discussion

Study 2 investigated refined Cutaneous Push feedback from the steering wheel. Overall recognition of patterns for Study 2 were at 77.35%.

> **H1** Perception accuracy of patterns drops with a) increasing number of active pins per pattern, b) immediate adjacency of pins, c) ipsilateral Cutaneous Push presentation rather than bilateral, d) locus of stimulus, e) unmirrored patterns bilateral patterns

H1.a was accepted as an increasing number of active pins in a pattern (1 stimulus: 89%, 2 stimuli: 80.43%, 3 stimuli: 77.35%, 4 stimuli: 65.1%) decreases pattern discrimination accuracy. Adjacency of pins influenced pattern perception accuracy significantly; **H1.b** was accepted. If pins in a pattern were adjacent to each other, 71.92% resulted in correct identification; whereas 81.79% were correctly recognised if the pins were not next to each other. P1 corroborates with "the two lower solenoids on each side are quite close together so it can be difficult to tell which one is being pushed out. Possibly move them a bit further apart". **H1.c** was accepted since presenting haptic patterns bilaterally increased identification accuracy from 79.24% to 80.83%. Since L1 and R1 were the most distinguishable pins in this study, and L2 and R2 the second most recognisable, hypothesis **H1.d** was accepted (Table 3.4). P5 commented with "I really liked the bit which gave feedback on the thumb - it was very clear if the thumb, palm, or both were receiving feedback - much easier than determining which of the two palm pins were pushing against me"; participant P8 simply said "not sure about the pins facing out" (i.e. L2/R2 and L3/R3); and P17 "anything involving the 3rd pin [was distracting]. Sometimes it's harder to tell between the 2nd and 3rd pin if I'm not paying attention". The collected and analysed data show that Cutaneous Push presented to the thumb region of the palm is highly effective and accepted by participants. Participants also mentioned repeatedly, that adjacent pins increased their efforts in distinguishing them from one another.

Hypothesis **H1.e** was accepted. Mirrored patterns resulted in 79.34% recognition accuracy and unmirrored patterns in 76.85%. P16 described it as "sometimes non-matching patterns either side were confusing" and P2 described it with "I was distracted the most where the pattern on one side did not match the pattern on the other, especially when there were both different number of pins and position."

L1	L2	L3	R1	R2	R3
96.52%	94.51%	90.20%	97.03%	95.29%	94.24%.

Table 3.4: Individual perception of the pins averaged over all participants.

H2 Cutaneous Push patterns presentation will not impact driving negatively

Hypothesis **H2** was accepted since there was no significant increase in lane deviation for any interval of time, *before*, *during*, or *after* pin presentation.

H3 Cutaneous Push patterns do not impact subjective effort negatively.

It is important to assess the usability and subjective impressions of an in-car infotainment system because these assessments indicate whether a driver is likely to use a system. Ten participants (strongly) agreed that Cutaneous Push is a pleasant and useful technique to present information to the driver. Future studies should aim at reducing the impact of Cutaneous Push feedback on perceived effort. A way of achieving this are potentially dynamically actuated solenoids; this will be investigated in Section 3.4.

Four of nineteen participants thought the haptic steering wheel could be very useful when combined with a navigation system, since visual feedback was considered distracting by 7/19 participants. 10/19 participants mentioned that the haptic — the "physical" — aspect of interaction was "nice" (P5). On the one hand, 7/19 participants recommended that the pins should be made stronger and more forceful. Participant P5 said "It would be ideal if the pins provided a bit more resistance, so that the feedback would be stronger" and P2 confirmed this with "the [patterns] were mostly perceivable, but on multiple occasions I would loosen my palm slightly just to confirm that none of the pins were being held down inadvertently."

It is interesting to notice, that despite an increase in feedback force between Studies 1 and 2, and despite the new force being above the 3.2N pain threshold [208], participants still perceived the solenoid push strength as not forceful enough. However, an increase in Cutaneous Push pressure will not be considered for future tests, because Bovenzi *et al.* [223] have shown that pressure $>=$ 5N to the palm starts to decrease blood flow to the fingers. This is enough reason to stay below 5N pressure force, as a numbing of the fingers is undesirable and can be detrimental to the driver's ability to control the vehicle.

3.3.5 Limitations

The Cutaneous Push steering wheel investigated in Study 2 was a refined prototype compared to Study 1. Study limitations were informed by the analysis of the collected data and user feedback. The first issue identified was that the NASA TLX data was not assessed after each block, but at the end of the experiment. This did not provide a conclusive answer to whether Cutaneous Push is or is not impacting mental efforts significantly. This mistake will be remedied in the future.

Participants commented on further two issues regarding the study design. Firstly, participants found the "[..] time lapse between sensing the pattern and keying it in too long [..]" (P2). However, the *after* pattern presentation interval is important to assess whether there are lasting effects of Cutaneous Push on driving. That is why it will not be amended for future studies. Secondly, participants P1, P2, and P13 agreed that "sometimes [it was] hard to pay attention as [the driving task] was a totally straight road with no distractions" (P13). As mentioned before, the aim was to measure the impact of Cutaneous Push on straight driving as this can give definite answer to whether the feedback technique has an effect.

Finally, participants P3, P4, and P6 commented that "the driver might grab the steering wheel in any place. Maybe provide this type of feedback in more places? (P19)". As the tested steering wheel is a prototype, the solenoids were only embedded into two locations on the wheel. If this technique is to be deployed into production vehicles, it can be implemented along the entirety of the wheel.

3.3.6 Summary

This section introduced Cutaneous Push feedback from a refined steering wheel. The three main aims of this experiment were to: (1) determine the characteristics of the most perceivable Cutaneous Push patterns; (2) the optimal physical setup; and (3) analyse which patterns impact driving performance and mental demand. These aims help to contribute an answer to the first research question of this thesis:

> **RQ1:** How effective is Cutaneous Push feedback from the steering wheel to the driver's palm (*Studies 1, 2, & 3*)?

Of the three hypotheses identified in Sections 3.2.2 and 3.3.2, all were accepted. The work in this section suggests that Cutaneous Push feedback can be an effective display in cars, conveying perceptible haptic patterns without negatively affecting driving performance. The following design recommendations can be given: (1) Cutaneous Push sensations should be presented to the thenar region of the palm to guarantee highest identification accuracy; (2) maximum number of pins per pattern should be three, otherwise perception is poor; and (3) presentation to both hands is better; especially, if patterns are mirrored.

3.3.7 Comparison of Study 1 and Study 2

Studies 1 and 2 followed the same methodology and similar hypotheses, but with a different apparati. Cutaneous Push from the first Study had an overall pattern recognition rate of 55.45%, and the refined steering wheel in Study 2 showed an improvement with overall perception performance of 77.35%. The results are a clear indication that the steering wheel changes from Study 1 to Study 2 impacted recognition performance positively. As can be seen in Table 3.5, individual pin perception improved.

Study	L1	L2	L3	R1	R2	R3
1st	91.16%	84.34%	86.08%	89.32%	87.31%	89.88%
2nd	96.52%	94.51%	90.20%	97.03%	95.29%	94.24%

Table 3.5: Individual perception of the pins averaged over all participants.

Study	Overall	1	2	3	4
1st	55.45%	88.29	68.00%	48.56%	36.03%
2nd	77.35%	89.4%	80.43%	72.58%	65.1%

Table 3.6: Averages of pattern perception depending on number of involved pins.

Both studies are consistent in their findings that 1) with increasing number of active solenoids, correct pattern perception decreases (Table 3.6); 2) adjacent pins in a pattern lead to worse recognition accuracy than non-adjacent pins; 3) bilateral patterns yield higher recognition accuracy; 4) especially if the patterns are mirrored across both hands.

The refined steering wheel design has shown great improvements over the first Cutaneous Push prototype. As no further physical changes will be made to the steering wheel, it is necessary to investigate if pattern recognition performance can still increase by presenting the patterns differently to the first two studies. Study 3 will look into *dynamic* patterns.

3.4 Study 3: Dynamic Cutaneous Push Feedback

The results of the first two studies have shown that force feedback through three solenoids in the steering wheel rim leads to high recognition rates and does not decrease driving performance nor increase workload. The patterns presented in these two studies were temporally *static*: the number of active solenoids does not change during feedback; if all pins on the left side of the rim (L1, L2, L3) are activated, then these three pins will push out of the rim at the same time, remain protruded for a set time, and finally retract simultaneously.

Dynamic Cutaneous Push pattern can be presented by displaying one pin after the other. For instance, to create a clockwise circular motion along the rim of the wheel, the pins L3, L2, L1, R1, R2, and R3 protrude sequentially. Research has shown that presentation of *dynamic* spatiotemporal tactile patterns — such as pushing out one pin after the other — result in higher recognition rates and quicker response times [11], as well as reduce task workload significantly [36]. Dynamic spatiotemporal notifications have been shown to exceed the performance of only spatially encoded patterns [224] because the limitations of spatial patterns can be overcome by applying time as another dimension to the stimulus. Dynamic patterns can offer a much richer stimulus set [224] as they allow users to interpret the tactile messages with familiar touch metaphors [36]. If well designed, dynamic tactile messages are a powerful tool for fast and effortless tactile pattern recognition.

This section investigates whether tactile illusions such as circular motion along the wheel are feasible by presenting a first investigation into the efficacy of dynamic Cutaneous Push feedback patterns, and their impact on workload, driving performance, and user preference. The aim was to gain insight into the feedback pattern which best supported recognition without compromising driving safety. Dynamic feedback patterns also broaden the Cutaneous Push vocabulary by extending previous work.

3.4.1 Research Aims

The aims of Studies 1 & 2 were to investigate 1) usability characteristics of perceivable Cutaneous Push feedback patterns, 2) physical characteristics, and 3) whether this technology impacted mental effort or driving performance. These studies, particularly the steering wheel design for Study 2, demonstrated that a limited number of static patterns have a high recognition rate such as 80.43% for presentation of patterns which were mirrored onto both hands.

Cutaneous Push technology can however be used to create more than *static* patterns. The solenoid pins can be activated one after the other, enabling *dynamic* motion on the surface by creating "illusions" of motion. However, this interaction technique needs to be tested first regarding its usefulness as in-car feedback, and its impact on driving and cognitive demand.

The three aims of Study 3 were to: 1) analyse the characteristics of dynamic Cutaneous Push patterns to understand their effectiveness; 2) evaluate the feedback design; and 3) to assess the amount of impact the dynamic patterns have on user workload and driving behaviour. These aims help to contribute an answer to the first research question of this thesis:

> **RQ1:** How effective is Cutaneous Push feedback from the steering wheel to the driver's palm (*Studies 1, 2, & 3*)?

3.4.2 Methodology

The Cutaneous Push steering wheel technology used for Study 3 is the same as in Study 2 (Section 3.3.2). Consequently, Apparatus and Measures are the same as for Studies 1 & 2 (Sections 3.2.2, 3.2.2).

Pattern Design

Twenty dynamic feedback patterns were investigated (Table 3.7). The aim of the individual pattern design was to maintain simplicity. Overly complex tactile patterns can increase distraction if the driver needs to redirect their attention away from driving to the presented feedback on their palm. During a pilot study, the twenty patterns investigated here were found to be simple and least distracting.

Two examples of dynamic feedback patterns will be described here: anti-clockwise circular motion (Figure 3.14) and sequential arrow to the left (Figure 3.15). Anticlockwise circular feedback is presented to both hands with pins L1, L2, L3, R3, R2, and R1 protruding sequentially one after the other, as can be seen below in Figure 3.14. Total pattern presentation duration was 1 second, ergo each pin was actuated for 167 ms (1000 ms / 6 pins). Each pin retracted before the protrusion of the next pin was initiated.

For the sequential arrow to the left pattern presented below in Figure 3.15, pins L2, L1, R1, R2 protrude from the steering wheel rim one after the other. Total duration of pattern

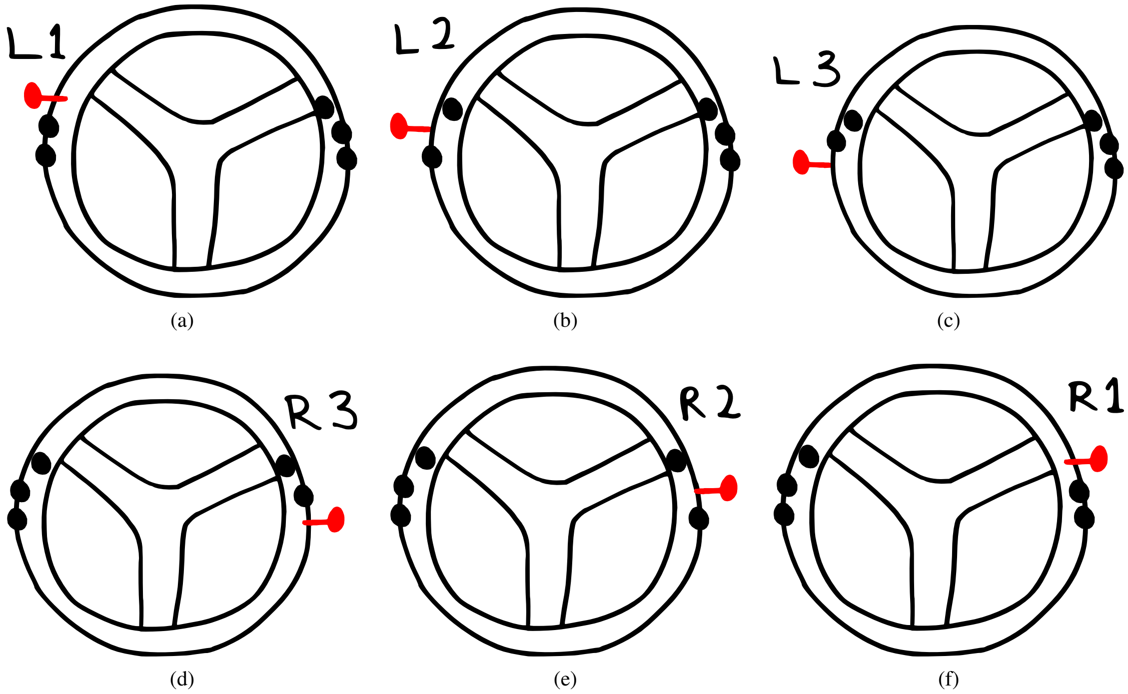


Figure 3.14: Representation of dynamic “anticlockwise circular” Cutaneous Push feedback. The sequence goes top left to bottom right. Pins are activated in following order: L1, L2, L3, R3, R2, R1.

presentation was 1 second, ergo each pin was displayed for 250 ms. Table 3.7 shows all 20 possible dynamic motions that were presented to the participants.

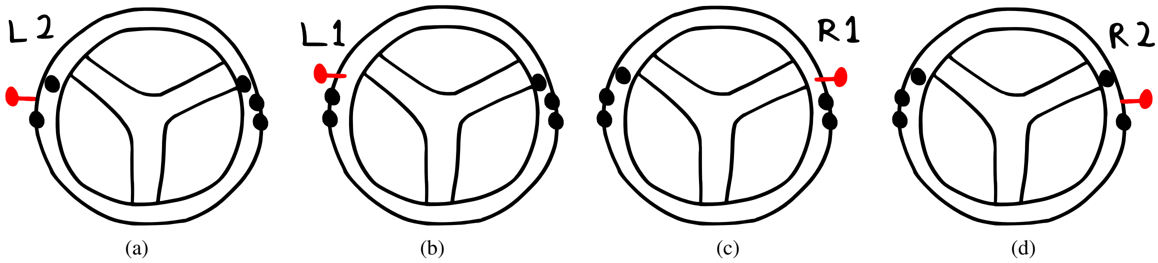


Figure 3.15: Representation of dynamic “arrow” Cutaneous Push feedback. The sequence starts top left to right. Pins are activated in following order: L2, L1, R1, R2. Each pin was actuated for 250 ms (1000 ms / 4 pins).

Cutaneous Push feedback is aimed to be used *during* mid-air gesture feedback to support the driver. For example, the driver receives feedback each time they execute a circle gesture correctly. If feedback duration lasts for two seconds (as it did for static patterns), total interaction duration can easily increase to the detriment of driver safety and user workload. Therefore, each animation lasted for 500 ms (Table 3.7 Rows 1, 3, 5, and Row 4 Columns 3 & 4), except for circular motions presented sequentially to both hands (Row 2 in Table 3.7) and sequential arrow motions which lasted for 1000 ms (Row 4 Columns 1 & 2 in Table

3.7). The choice to present feedback for 500 ms and 1000 ms was motivated by Hwang *et al.* [11] who presented three vibrotactile stimuli sequentially on the steering wheel for 450 ms. A pilot test assessed whether 500 ms is a sufficient time frame to display three Cutaneous Push stimuli presented sequentially. The result was that 500 ms are sufficient for users to differentiate the dynamic patterns. For purposes of simplified discussions and analysis, the dynamic feedback motions were further classified into seven *Families* (Table 3.7):

Hypotheses

A pilot study informed the formulation of the hypotheses, as well as results from studies 1 & 2 on static Cutaneous Push feedback in driving situations (Section 3.2, 3.3).

- **H1** Perception accuracy of patterns will differ between the Families of motions;
- **H2** Cutaneous Push patterns will not impact driving negatively;
- **H3** Cutaneous Push patterns do not affect workload negatively.

H1 anticipates a difference in recognition accuracy for the seven families of motion. The pilot study results showed that circular motions presented to one hand and presented sequentially will have highest perception performance. Based on findings from Studies 1 & 2, mirrored patterns such as in Table 3.7 Row 4 are expected to result in high correct identification because redundantly displayed information confirms perception [225].

Similar to static Cutaneous Push feedback, **H2** does not expect an impact of the feedback on driving performance. Based on the literature discussed above (Section 3.4), **H3** does not predict any effects of the feedback on user workload. Well designed spatiotemporal *dynamic* tactile feedback allows the user to interpret the tactile messages with familiar touch metaphors, resulting in fast and effortless tactile pattern recognition.

Procedure

Upon arrival, participants were briefed about the study and and given an introductory training session. During this introduction, participants were shown the feedback patterns and were instructed on how to classify the perceived pattern according to the scheme above (Figure 3.7). Following this, participants were provided with a single driving session where each pattern was presented randomly (Balanced Latin Square order). After each pattern presentation, they were asked to classify the pattern according to the table of motions (Figure 3.7).

The main experiment was designed exactly like the initial training. During the actual study however, all 20 patterns were presented in 4 randomly ordered blocks. A single trial consisted of 6 seconds of driving (i.e. the *before* interval), 500 or 1000 ms of pattern presentation

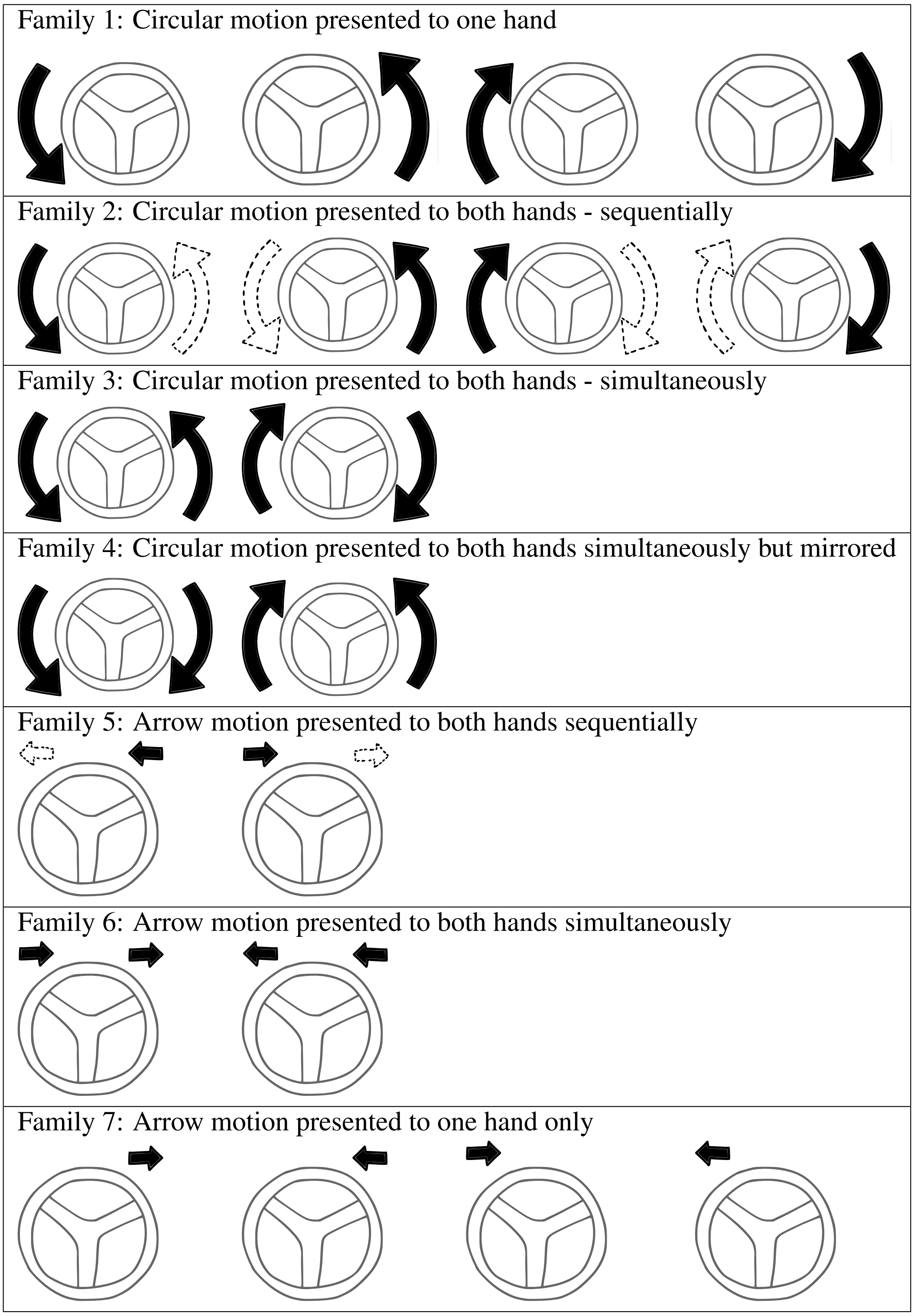


Table 3.7: Grid of feedback patterns. Black: presented first; dotted: presented second.

(*during*), 5-7 seconds of post-pattern-presentation driving (i.e. *after* interval), and finally a break where pattern classification was conducted. During pattern classification, participants used the mouse provided to click the image of a possible pattern, which represented the perceived motion (Figure 3.16). The *before* and *after* pattern presentation periods are important to allow the driver 1) to regain stabilised driving and 2) measure the impact of the feedback on driving behaviour. That reasoning resulted in an increase of *before* and *after* intervals to six seconds (from four; *before*) and five to seven seconds (from three; *after*) pattern presentation.

Figure 3.16: Feedback form for dynamic Cutaneous Push feedback. Participants clicked the box next to each design.

The laboratory setup was similar to Study 2 (Figure 3.8). The participants sat in a padded chair in front of a 27 inch LCD monitor and a PC running the OpenDS simulator. Drivers were able to steer in the simulation using the refined steering wheel from Study 2, attached to a Logitech G27 Racing Wheel base. Participants wore Phillips SBC-HP 200 headphones to mask any sound from the solenoids. Road and car noises from the driving simulator were played through the headphones.

Participants

Twelve participants (six female) aged between 19 and 36 years (μ=24.4, σ=5.3) were recruited via the University of Glasgow's student online forum. Of these 12, nine participants obtained their driving license in a country with Left-Hand-Traffic (LHT) and three a Right-Hand-Traffic (RHT) license. None of the participants had prior experience with cutaneous push feedback. One participant was left handed. The participants were paid £10 at the end of the study.

3.4.3 Results

Recognition

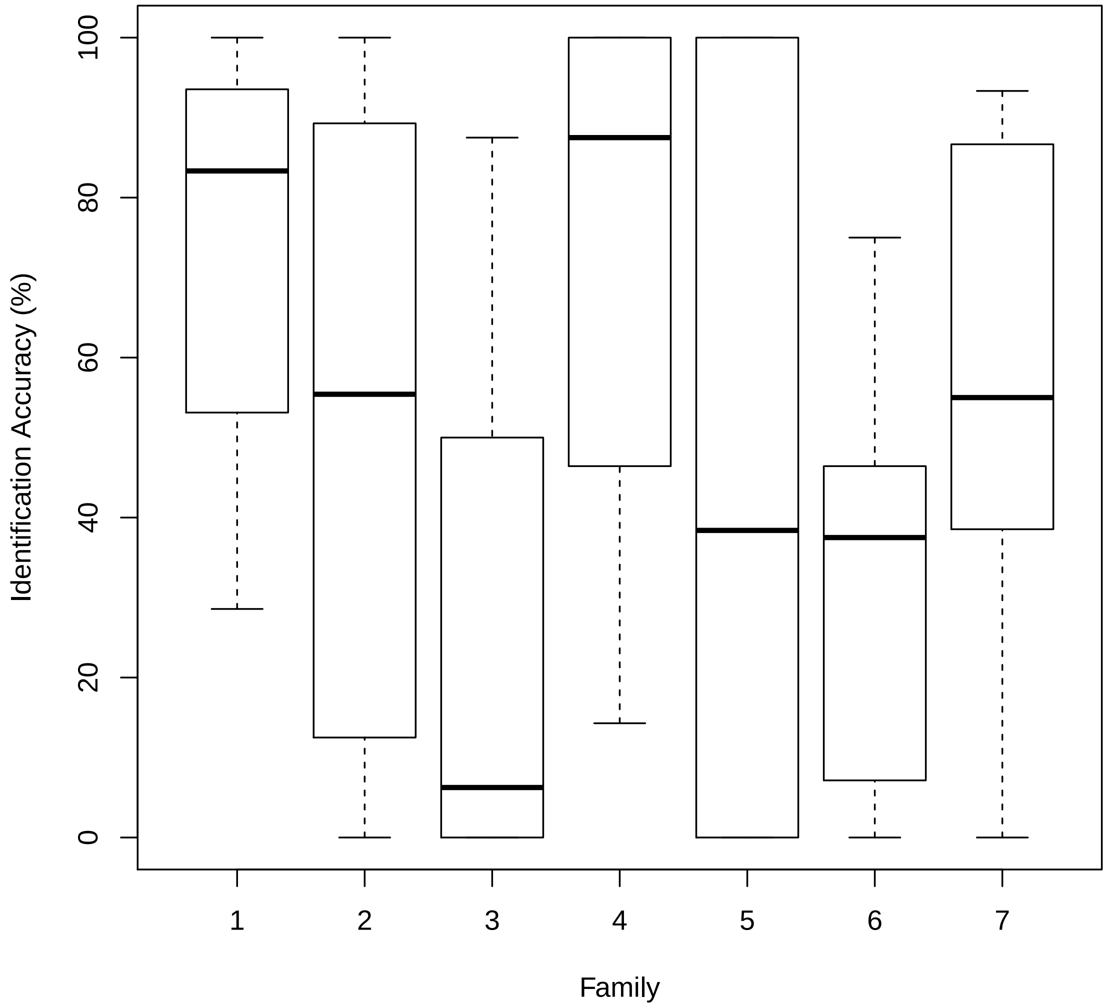


Figure 3.17: Success rate of the dynamic Cutaneous Push patterns grouped by Family.

Overall recognition performance was 51.46%, with highest performance in circular motion to one hand 73.51% and lowest in circular motion presented to both hands simultaneously 25.27% (Figure 3.17). An ANOVA on a binomial regression model found a significant main effect of Family pattern on recognition performance: $chi^2(7) = 2.934, p = 0.003$ (Figure 3.17). A *post hoc* Tukey test revealed that circular motion to one hand and circular mirrored patterns had significantly higher recognition success than the other families of feedback patterns ($z = 2.934, p = 0.003$).

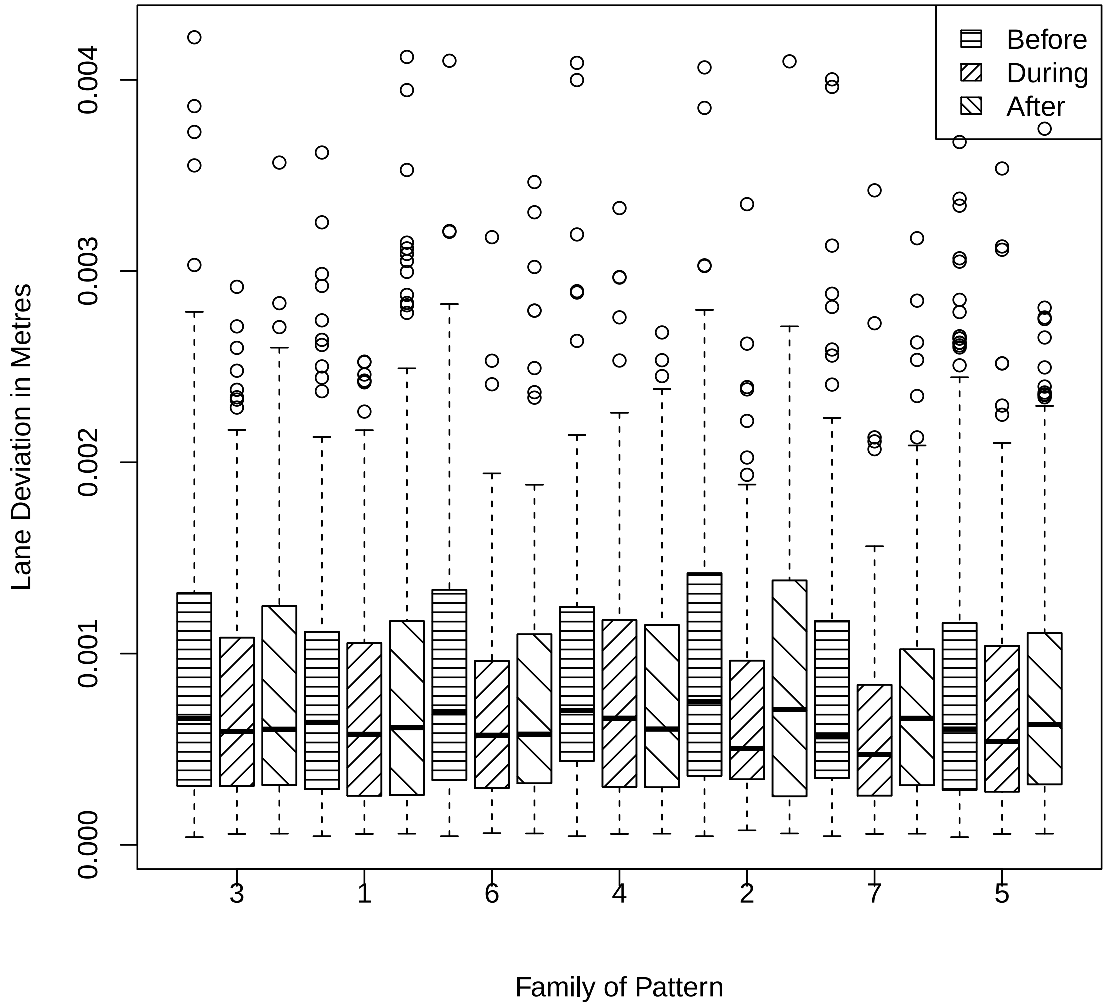


Figure 3.18: Lane deviation *before*, *during*, and *after* dynamic Cutaneous Push pattern presentation (grouped by Family).

Lane Deviation

Driving data was non-normally distributed for *before* ($W = 0.849, p - value < 0.001$), *during* ($W = 0.860, p <= 0.001$), and *after* ($W = 0.863, p <= 0.001$) driving intervals — as shown by Shapiro-Wilk normality tests. A MANOVA was conducted to test the hypothesis whether Family of motion impacted lane deviation (*before* ($F(1,3) = 0.051, p = 0.821$), *during* ($F(1,3) = 0.152, p = 0.697$), and *after* ($F(1,3) = 0.006, p = 0.936$)).

Qualitative Data

A MANOVA test showed there was a significant impact of learning effect on perceived workload ($\chi^2(1) = 4.933, p = 0.031$), with the last block of the study resulting in the least negative impact ($\chi^(1) = 7.347, p = 0.009$). The more experienced user gained with the system, the less mentally and temporally demanding they perceived dynamic Cutaneous Push feedback, as well as experienced less effort and frustration (Figure 3.19).

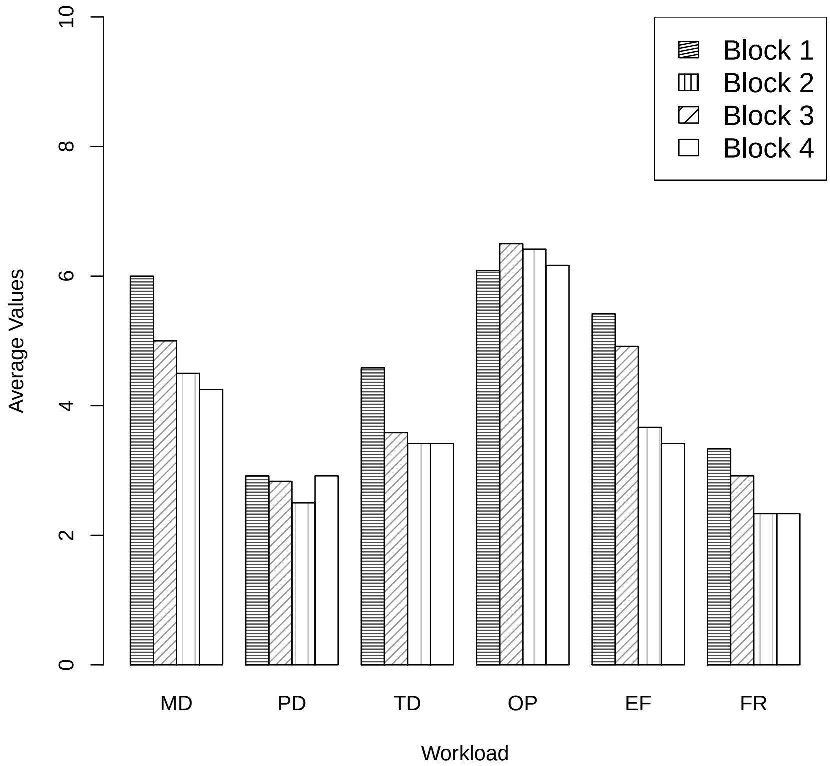


Figure 3.19: Average results of the NASA TLX questionnaire. MD: Mental Demand, PD: Physical Demand, TD: Temporal Demand, PE: Performance, EF: Effort, FR: Frustration.

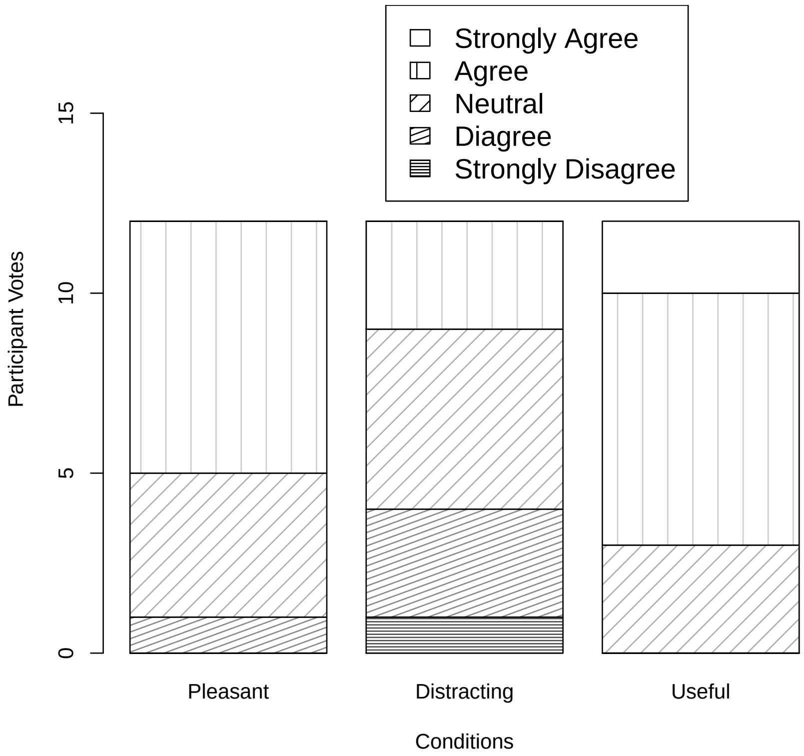


Figure 3.20: User feedback on how pleasant, distracting, useful Cutaneous Push feedback is perceived.

3.4.4 Discussion

For in-car gesture feedback to be successful, it needs to support interaction whilst importantly not having a negative impact on the driver's workload and control of the vehicle. Study 3 investigated the efficacy of *dynamic* Cutaneous Push feedback on the steering wheel during a simulated driving task, comparing seven types of feedback patterns against each other. This study showed that dynamic Cutaneous Push notifications such as circular clockwise to one hand (73.51% recognition accuracy) and mirrored to both hands (71.91%) are an effective way of delivering messages to the driver.

H1 Perception accuracy of patterns will differ between the Families of motions

Overall dynamic pattern identification performance was at 51.46%. There were significant differences in pattern recognition accuracy between the Families (Table 3.8); **H1** was accepted. For instance, circular patterns presented to one hand (Family 1) resulted in recognition accuracy as high as 73.86% whereas circular patterns presented simultaneously to both hands (Family 3) resulted in 25.27% accuracy. As expected, if Cutaneous Push stimuli were presented simultaneously onto both hands (Family 3; Table 3.7 Row 3), perception of the stimuli presented to the hands overwrote each other. Participant P6 commented that "simultaneous rotation and simultaneous left to right/right to left" were the most distracting patterns. However, if the patterns were mirrored across two hands (Family 4), perception was increased (71.91%). Redundant presentation of information to both hands improved pattern recognition performance.

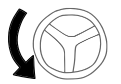
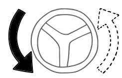
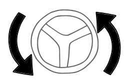
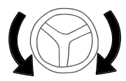
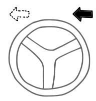
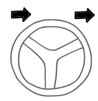
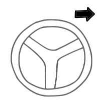
Family	1	2	3	4	5	6	7
							
Accuracy	73.51%	51.08%	25.27%	71.91%	47.19%	34.44%	56.83%

Table 3.8: Individual perception of the Families of motions averaged over all participants. The patterns in the columns are representatives of each Family.

The average for arrow motion recognition was 51.42%. Interestingly, patterns consisting of two stimuli (such as single arrow patterns; Family 7) were perceived as "too fast" by participants, while three stimulus patterns (Family 1) were described as "perfect, no need to change" (P3). The *perceptual space-time distortion* [226] phenomenon describes how three stimuli in 500 ms are not identified as too fast and two stimuli are; even though two stimulus patterns had more display time (each 250 ms) than three stimulus patterns (each 167 ms). Goldreich [226] explained that short stimuli displayed in rapid succession onto one body site (e.g. left arm) perceptually "expand" the time elapsed between consecutive events and "reduce" the distance between stimulus origins. This can be explained with the following two assumptions: 1) if stimuli are placed close to each other, and displayed in short intervals, the stimuli can be perceived as if they originate from the same source; and 2) objects which contact the skin tend to move slowly.

The second assumption is very important to understand as it might explain the poor arrow pattern recognition which was observed in this study. Because objects which contact the skin are assumed to be slow, two, temporally close taps on the skin might have been interpreted as originating from the same source; that is, "the object that tapped me, is still in the same place". However, three quick taps along the skin are against the expectation that the object is slow, therefore the velocity perception of the object is reconciled with the expectation; that is the object and its taps along the skin are not perceived as quickly as they factually were. The *perceptual space-time distortion* phenomenon explains how two tap patterns (single hand arrows; Family 7) are perceived as too fast, as well as their poor perception accuracy.

Interestingly, sequential arrows (Family 5) had worse recognition accuracy than single hand arrows (Family 1). The overall longer display duration of 1000 ms did not support recognition. The *perceptual space-time distortion* might have acted doubly. Two perceptual distortions took place, one on each hand; instead of two arrow motions per hand supporting each others' perception. Participant P12 emphasised that "the single-hand patterns were amazing, I could definitely perceive them with little mental effort and they felt natural as well".

H2 Cutaneous Push patterns will not impact driving negatively

H3 Cutaneous Push patterns do not affect workload negatively

No impact of dynamic Cutaneous Push was observed on either driving performance, nor on workload; **H2** and **H3** were accepted. Analysis of the NASA TLX questionnaire showed that over time, participants experienced significantly less mental demand, effort and frustration with the feedback technique.

Overall, participants were very positive about dynamic Cutaneous Push notifications. Participant P2 said "I would rank this [technique] very highly and [as] very useful". In the open-ended questionnaire, users were asked to consider Cutaneous Push with infotainment feedback techniques they are already familiar with. Participants compared dynamic Cutaneous Push with vibration from the steering wheel and ranked Cutaneous Push consistently higher. One participant described it as "I think its a good method of feedback, vibration would be slightly stressful to some users. [...] I think this method would be the safest in terms of distraction" (P5). Others described the feedback as "I still found this feedback much nicer and less distracting than vibration on the steering wheel" (P12) and "Probably between vibration and audio - easier to feel than vibration" (P7). A future study could look into a qualitative comparison between vibrotactile steering wheel feedback and Cutaneous Push in terms of urgency, valence, and message content. It is worthwhile to investigate Cutaneous Push notifications further because they can deliver rich information without negative impact on driving performance nor workload. In general, participants were so positive about this technique, they provided many ideas for practical applications, which shows the potential of Cutaneous Push for in-car usage. P3 said "I would rank this feedback as number one. The sensation when the solenoid push the palm is different compared with the others. It somehow gives me a sensation to keep focused". Other suggestions were: Cutaneous Push messages can be used to warn the driver about sleepiness and drowsiness (P3), as navigational assistance (P1), about hazards and speed cameras (P2), and "[...] this could be used to draw my focus to the gauge cluster" (P6).

3.4.5 Limitations

A key difference between Study 3 and the previous two studies was that feedback display duration was reduced to 500 ms (max 1000 ms) compared to Studies 1 & 2's 2000 ms duration.

This change was motivated by the aim of this thesis: to help drivers during gesturing, and Cutaneous Push feedback may be a technique which can support interaction. However, to do so, it cannot elongate interaction by presenting feedback for two seconds; it needed to be shortened. Consequently, a key aim of this study was to assess whether dynamic Cutaneous Push patterns were perceivable in 500 ms. As discussed above, three stimuli per pattern were perceived well within 500 ms.

The assessment of workload for each pattern did not result in a high information content. If workload would have been assessed after each Cutaneous Push presentation instead of after each block (i.e. 20 messages), it would have been possible to analyse the workload of each pattern. This is a limitation of this study. Finally, it is acknowledged that twelve participants is not a lot. Future studies will aim to have twenty users.

3.4.6 Summary

This study investigated *dynamic* Cutaneous Push feedback on the steering wheel. Participants found dynamic Cutaneous Push design especially useful. The aims of this experiment were to: 1) compare dynamic Cutaneous Push patterns to understand their effectiveness; 2) evaluate the feedback design; and 3) to assess the amount of impact the dynamic patterns have on workload and driving behaviour. These aims helped to contribute an answer to the first research question of this thesis:

> **RQ1:** How effective is Cutaneous Push feedback from the steering wheel to the driver's palm (*Studies 1, 2, & 3*)?

Of the three hypotheses identified in Section 3.4.2, all were accepted. This study shows that dynamic Cutaneous Push patterns have a high acceptance rate amongst users and can be recognised with up to 73.51% recognition accuracy without negatively impacting driving. The following design recommendations are proposed as a result from the analysis: 1) feedback pattern should be presented to one hand for high recognition rate; 2) if presented to both hands, then the patterns should be mirrored in the same direction; and 3) a pattern should consist of three tactile pressure points per pattern.

3.5 Conclusions

This chapter investigated Cutaneous Push feedback from the steering wheel through three experiments. Study 1 introduced Cutaneous Push as a means of interaction feedback in driving situations. It looked into perceivability of *static* Cutaneous Push feedback. Analyses into

(1) the characteristics of the most perceivable Cutaneous Push patterns and (2) the optimal physical setup revealed that Cutaneous Push can be a very useful feedback technique.

Study 2 investigated the same questions as Study 1, however with a refined feedback system. The steering wheel was upgraded to production car size, the solenoids provided stronger push force, they were given plastic domes, and the pins were rearranged to provide feedback to the thumb region on the palm. These changes allowed for much higher pattern recognition accuracy from 60.2% to 77.35%. Studies 1 & 2 established a relationship between the number of actuated solenoids and pattern identification. Namely, perception accuracy drops with increasing number of pins, and is very poor above three active solenoids (for > 3 pins, Study 1: 36%, Study 2: 65.1%), and patterns need to be mirrored symmetrically across both hands if multiple pins are involved.

Both of these studies looked at *static* patterns, whereas Study 3 investigated the effects of *dynamic* Cutaneous Push feedback. The two major differences between Study 3 and the previous studies were: 1) sequential display of stimuli (i.e. dynamic), and 2) shorter display time. In Studies 1 & 2, each pin was displayed for 500 ms, and the more pins were presented, the longer the total display duration. For instance, patterns consisting of 4 pins were presented for 2000 ms. Dynamic patterns however were presented for a total of either 500 or 1000 ms. This reduction in display time is necessary if the Cutaneous Push patterns are to support mid-air gesture interaction. Elongated feedback only increases interaction duration, which may impair driver safety. Despite these changes, perception accuracy was high for circular patterns presented to one hand 73.51% and mirrored patterns 71.91%. Participants agreed that particularly dynamic Cutaneous Push was a useful feedback alternative to current techniques such as visual, auditory, and vibrotactile. It is important that users enjoy using an interface, because no matter how safe a particular interface might be, if the majority of user do not adopt it, it is irrelevant [227].

Looking at Cutaneous Push feedback from a practical perspective yields the benefit of discrete message delivery. These messages can include warnings about blind spots, upcoming road conditions, and pedestrians. Navigation information can also be conveyed reliably to the tactile channel due to the encoded spatial information [228]. As shown by Di Campli San Vito *et al.* [8], Cutaneous Push yields high accuracy as a navigational tool because it captures a person's spatial attention, by presenting information from the same direction as the driving event [156]. It is easy to envisage single actuator patterns being used for time-critical messages (e.g. cyclists in blind spots), and multiple actuator patterns for more complex and non-time critical messages (speed cameras, low fuel tank, road surface conditions, driving performance, etc.).

3.5.1 Research Question 1

It is important to provide feedback to the driver to keep them informed; however, the feedback should not be cognitively demanding, nor impact driving behaviour. The findings in this chapter suggest that novel Cutaneous Push is a valid alternative for non-visual feedback in driving situations. The outcomes of the experiments are now summarised as recommendations in response to the following research question:

> **RQ1:** How effective is Cutaneous Push feedback from the steering wheel to the driver's palm (*Studies 1, 2, & 3*)?

Cutaneous Push notifications are most effective if they are presented: 1) *dynamically*; 2) to one hand only; and 3) if they are presented to both hands, they should be mirrored.

3.5.2 Contributions

The research in this chapter makes the following contributions:

- It presents a novel tactile feedback technique for in-car interaction, namely *static* and *dynamic* Cutaneous Push feedback;
- It investigates different physical setups of the Cutaneous Push steering wheel, and their implications for recognition, workload, and driving behaviour;
- It finds that Cutaneous Push feedback has high user acceptance; especially dynamic Cutaneous Push.

Chapter 4

Unimodal Feedback for Mid-air Gestures in Cars

4.1 Introduction

Feedback is necessary to help users understand mid-air gesture sensing systems [52]. Feedback informs the user whether the system pays attention to them, classifies the executed gesture correctly, and provides the user with knowledge about system state. This information is necessary to avoid increased mental efforts. As discussed earlier in this thesis, there is growing necessity for multimodal feedback as there is a growing interest in mid-air gesture interaction in cars (Sections 2.4 & 2.5). Multimodal feedback supports the mid-air gesture interaction as well as supports in-car infotainment interaction in cars without negatively affecting the driving task. Feedback allows for coupling of the user's hand to the interface [39] and provides a sense of control over the touchless interface [35]. This increases user satisfaction, safety and usability of gestures [40]. Current mid-air gesture systems in cars only give limited and mainly visual feedback. If drivers need to take their eyes off the road to understand their interactions with the car, then the benefits of mid-air gestures are not being fully realised. Non-visual feedback is ideal for in-car gestures: visual attention can remain on the road whilst information about secondary tasks (i.e., interacting with the in-car systems) is offloaded to other sensory modalities [41].

This chapter investigates the use of auditory and Cutaneous Push feedback for in-car gestures, as well as novel visual feedback in the driver's visual periphery [31], intended to allow them to keep their eyes on the road [17]. This chapter aims at answering the following Research Question:

> **RQ2** How do *unimodal* mid-air gesture feedback techniques influence driving performance and in-car interaction (*Experiment 4*)?

The Literature Review (Section 2.5) and the previous Chapter (Chapter 3) showed that auditory, Cutaneous Push, and peripheral vision are effective means of communication during in-car interaction. Auditory feedback is a high resolution modality which has been shown to be beneficial for many applications. The focus of this chapter is on unimodal feedback, in particular, to provide a well studied basis for future multimodal applications. Study 4 presents the effects of different types of feedback for in-car mid-air gestures: (1) Auditory feedback; (2) Peripheral Lights feedback; and (3) Cutaneous Push feedback. The impact of novel unimodal feedback on visual distraction (gaze away from the road), car control (lane deviation), gesturing performance, and cognitive workload was studied.

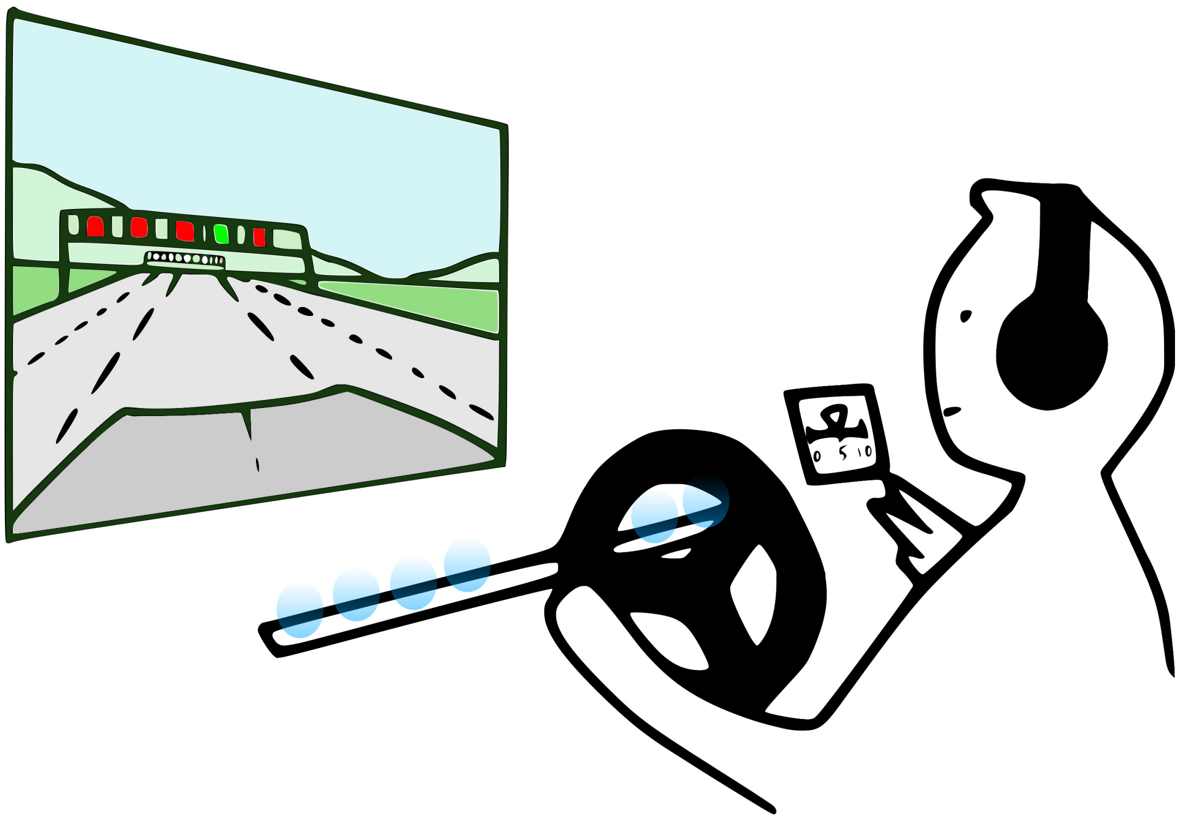


Figure 4.1: Sketch of experiment set-up. From left to right: 5 lane motorway projected onto wall; LED strip for Peripheral Lights feedback; steering wheel with Cutaneous Push feedback; 8 inch screen for Visual feedback; headphones for Audio feedback. In this scenario, the participant is gesturing Victory with their right hand above the gear stick.

In this thesis, the focus is on simple mid-air hand movements, likes swipes and poses, rather than user interface controls like buttons and sliders used in previous in-car research [79, 38, 80]. Simple movements are more representative of how production cars utilise gestures and are intended to further reduce distraction, using input to simply invoke actions rather than precisely control quantities (as with sliders and dials).

4.1.1 Chapter Structure

Section 4.2 introduces the Research Aim and the Research Question for this chapter. Section 4.3 describes the design of unimodal feedback techniques. Section 4.4 presents the results and Section 4.5 discusses these and the limitations of the experiment and the presented techniques. Section 4.6 gives conclusions and revisits the research question discussed earlier in this chapter.

4.2 Research Aims

A study was designed to investigate the effectiveness of four different types of feedback for four different mid-air gestures in a simulated driving environment. The key aim was to gain insight into the feedback modality which distracts the driver least from the primary driving task and supports gesture interaction.

The first aim of this study was to measure the impact of feedback modality for gestures on driving safety. In the context of this thesis, driver safety is measured through driving performance, eyes-off-the-road time, and perceived workload. It is of utmost importance to understand whether and which feedback type affects driver safety to eliminate negative impact factors. Since this study looked at feedback for mid-air gestures, the effects of feedback modality on the gesturing performance were studied as well.

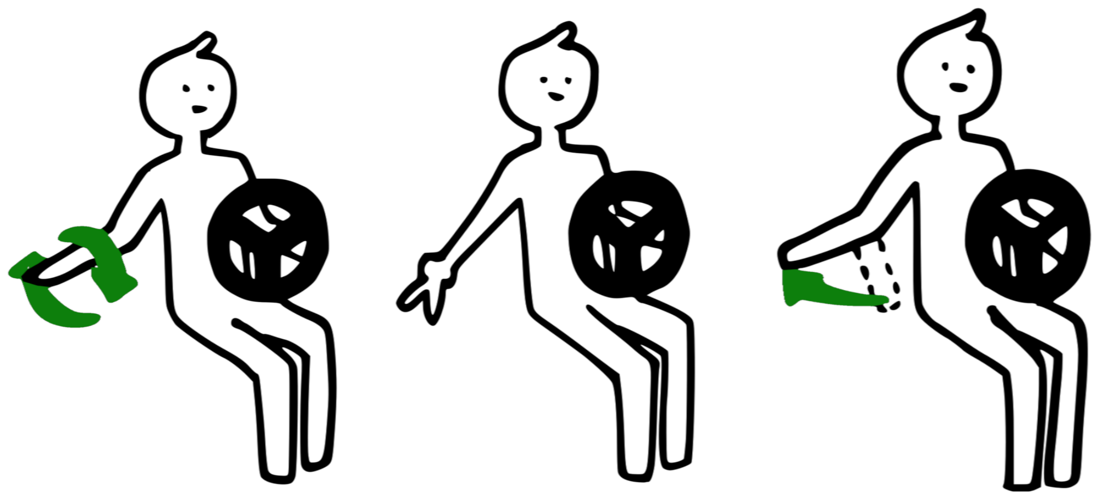
The three main aims of this experiment are to: (1) determine which feedback type has least impact on driving and gesturing performance, eyes-off-the-road time, and driver workload; (2) investigate the impact of gesturing in mid-air on driving safety; and (3) analyse which feedback modality has highest user acceptance. These aims begin to contribute an answer to the second research question of this thesis:

> **RQ2:** How do *unimodal* mid-air gesture feedback techniques influence driving performance and in-car interaction (*Experiment 4*)?

4.3 Methodology

4.3.1 Gestures

An existing set of gestures was used based on in-car mid-air gesture design guidelines [229, 104] and ones already available for in-car use (BMW, VW) (note: this study was conducted at the end of 2016; there are more in-car gestures being utilised now). VW introduced mid-air swipe left/right in their gesture enabled user interface [27], which was used in this study (Figure 4.2 right). BMW use a circular motion to increase/decrease a selection. The participants had to perform a circular motion with an extended index finger either clockwise (increase) or anticlockwise (decrease) (Figure 4.2 Left). The victory gesture (extended index and middle fingers) was also introduced by BMW and adopted here (Figure 4.2 middle). Its purpose is to turn the system / display screen on or off.



(a) (b) (c)

Figure 4.2: The three types of gestures used in our study. From left to right: circle, victory, swipe. Participants were asked to gesture with their right hand above the gear stick.

The following types of mid-air gestures were used: Circle Clockwise 2, 3, 4 times (CW2, CW3, CW4), and Circle Anticlockwise 2, 3, 4 times (ACW2, ACW3, ACW4), Victory (V), Swipe Left 2, 3, 4 times (SL2, SL3, SL4), and Swipe Right 2, 3, 4 times (SR2, SR3, SR4). The gestures were differentiated depending on hand posture and arm movement, not the number of executions, thus the gesture set consists of five different gestures (SL, SR, V, CW, ACW). Previous research suggests the use of four to eight gestures for in-car gesture interaction [110, 2, 111]. The choice to start with two gesture executions (e.g. CW2) rather than one (CW1) was due to two reasons: 1) in a real world scenario, it is highly unlikely that the user would increase the volume by one unit, or decrease the temperature by 1 degree Celsius; and 2) in order to keep the swipe motions comparable to the clockwise motions, they too started with two executions of the same motion.

A gesture interaction consists of three parts: the gesture, the execution time, and feedback time. The duration of a single gesture consists of 750 ms execution time and up to 500 ms for gesture feedback. For example, a single swipe motion lasts for at least 750 ms. If the participants were instructed to execute a circle clockwise four times (CW4), the duration of the interaction is at least 3600 ($4x750$ ms gesture execution and $4x500$ms feedback) ms long (Table 4.1). The Leap Motion controller [4] was used for gesture recognition of swipe and circle gestures. The victory gesture was detected by extending the index and middle finger for 750 ms dwell time.

In this thesis, the gestures were performed with right hand only (as if the car was driving on the right). The gestures were distinct motions completed above the area where the gear stick is located (Figure 4.3).

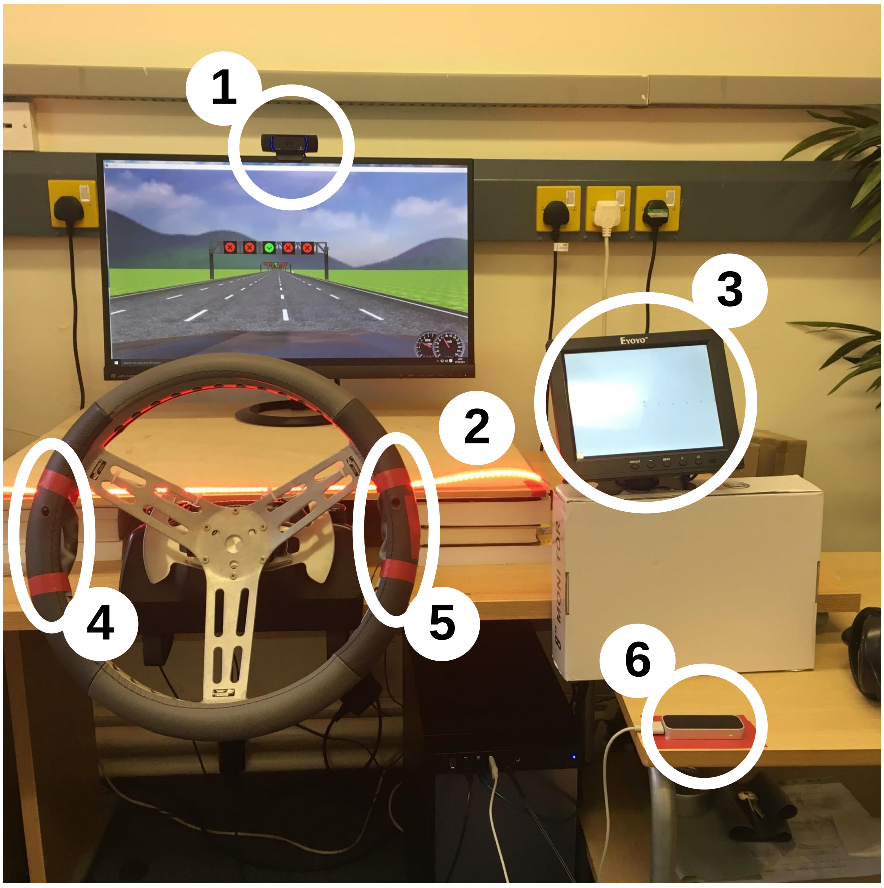


Figure 4.3: Experimental Setup. The placements of the individual devices were guided by the measurements of a Jaguar Landrover Discovery Sport. 1: webcamera, 2: LED strip, 3: centre console monitor, 4: Cutaneous Push feedback [20], 4: capacitive sensor, and 6: Leap Motion sensor.

4.3.2 Feedback Design

As found by May *et al.* [98] and during pilot studies, participants were prone to making accidental gestures by entry of sensing area above the Leap Motion (i.e. interaction box). Thus the system was implemented such that feedback was only provided to the expected gesture types for the current task. If a circular motion was expected, only CW and ACW motions caused system reactions. This allowed participants to make mistakes but did not trigger unwanted system responses [104].

Alignment feedback was presented *after* gesture execution in a *discrete* manner instead of presenting it during the execution and continuously. Continuous feedback is important for usability [104, 34], however it can increase task duration and visual demand. [116].

Visual Feedback

Visual feedback (VF) was provided on the centre console screen to the right of the participant (Figure 4.3). VF functioned as baseline for the other feedback conditions. VF was chosen because it is the most common feedback type in combination with mid-air gestures in cars (e.g. BMW, VW, etc). The GUI design was adapted from the Jaguar Landrover Discovery Sport's GUI [230] in terms of the size of the screen, size of text, etc. Figure 4.4 show the GUI which consisted of a horizontal single scroll bar (from -5 to $+5$). Zobl *et al.* [129] used a horizontal alignment of the bar since swiping motions were performed horizontally. Further, the horizontal bar resembles VW's mid-air gesture GUI in which a swipe left motion moves a song cover from the right to the left to the next song. In this GUI, SL and SR shift the scale of the bar in either direction (SR1: -6 to $+4$, SR2: -7 to $+3$), maintaining the cursor in the centre of the screen (mimicking VW's song swipe); successful CW and ACW motions result in increase/decrease of the cursor on the scale; and V turns the screen on / off.

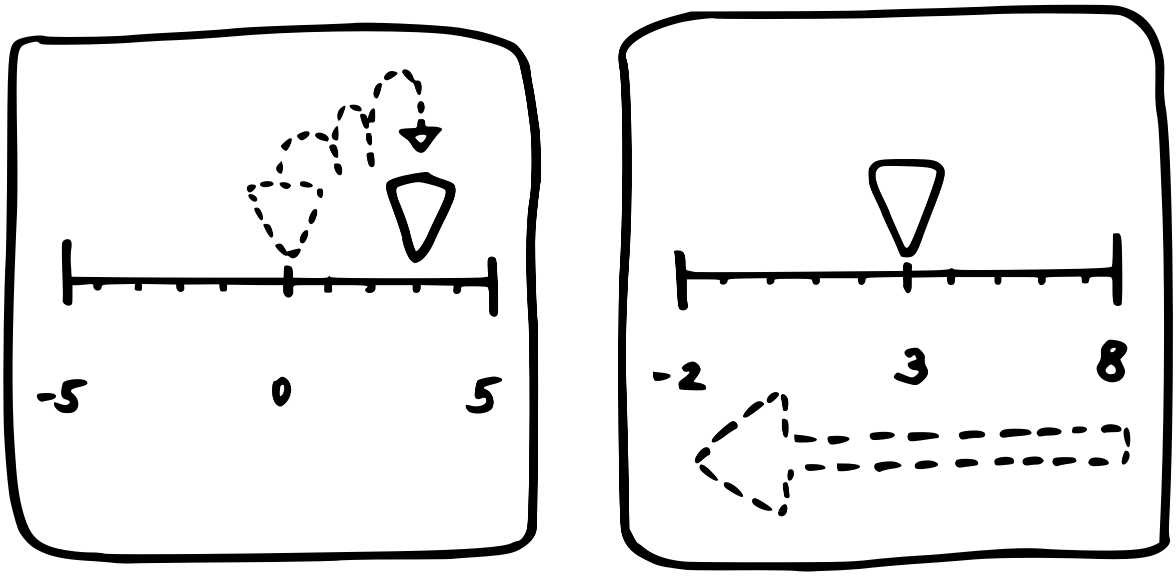


Figure 4.4: The 8 inch centre console screen for Visual feedback. Left: change in cursor position after three Circle Clockwise motions. Right: change in scale labels after three Swipe Left motions.

Auditory Feedback

Auditory feedback (AF) was presented via Earcons [138]. The tones used were generated in Audacity [231] and guided by Freeman's audio feedback [34] (Table 4.1). After a gesture was recognised by the system, Audio feedback was presented immediately. Each gesture had a distinct Auditory feedback. Feedback for the V gesture were Windows XP hardware insert/remove sounds. The entire duration of the feedback was 500ms. SR feedback was a double beep at C5 frequency which lasted a total of 350ms, and feedback for SL was a double beep at C4. Feedback for the clockwise circular motion was the increase of the note by an octave, and decrease by an octave for the anticlockwise motion. The feedback for the circular motions lasted 500 ms.

Gesture	Tone	Duration	Time b/w notes
V on	g#4 $\rightarrow$ c5	2 x 225 ms	50 ms
V off	c5 $\rightarrow$ g#4	2 x 225 ms	50 ms
SL	c4 $\rightarrow$ c4	2 x 150 ms	50 ms
SR	c5 $\rightarrow$ c5	2 x 150 ms	50 ms
CW	c4 $\rightarrow$ b4	500 ms	-
ACW	b4 $\rightarrow$ c4	500 ms	-

Table 4.1: This table shows the Auditory feedback used for each gesture. The arrow in Tone describes the transition from one note to the next. Duration describes the length of each note.

Tactile Feedback

Tactile cues were presented via Cutaneous Push feedback (CPF) from the steering wheel and to the driver's left palm. The steering wheel from Studies 2 & 3 was used (Figure 3.8). The pin L1 presents Cutaneous Push feedback to the thenar/thumb region, L2 and L3 provide feedback to the median palmar region (L2 behind the index finger; L3 behind the little finger). Cutaneous Push feedback was displayed for the same amount time as the other techniques. Feedback for the V gesture presented all pins at the same time to the palm (72.25% recognition success in Study 2). Feedback for the SL motion was a double poke of the L2 pin with a gap of 50ms (total 350ms). It was presented to the L2, because it is the left-most pin and therefore a 'mirror' of direction of the swipe left gesture. Feedback for SR was the sequential display of L1 (because it is the right most pin). This feedback resembles the double beep feedback from the Audio condition. Feedback for the circular motion mimicked the circling hand: if the driver circled clockwise, the Cutaneous Push feedback presented L3 $\rightarrow$ L2 $\rightarrow$ L1 (73.51% recognition success in Study 3). Each presentation lasted 166ms, totalling 500ms (Table 4.2). The aim was to have similar duration for each single pin presentation for each gesture; thus pins were presented 150-166 ms.

Gesture	Pins	Duration	Time b/w Pins
V	all	150 ms	-
SL	L2 $\rightarrow$ L2	2 x 150 ms	50 ms
SR	L1 $\rightarrow$ L1	2 x 150 ms	50 ms
CW	L3 $\rightarrow$ L2 $\rightarrow$ P1	3 x 166 ms	-
ACW	L1 $\rightarrow$ L2 $\rightarrow$ P3	3 x 166 ms	-

Table 4.2: This table shows the Cutaneous Push feedback used for each gesture. The arrow in Pins describes the transition from one feedback location on the palm to the next. Duration describes the length of each pin presentation.

Peripheral Lights Feedback

The Peripheral Lights feedback (PLF) displayed on a single LED strip from the A-pillar on the left side of the driver to the beginning of the centre console (Figure 4.3). The strip was placed behind the steering wheel where the car instrument cluster would be (as proposed by Löcken *et al.* [17]).

Feedback for the V-on gesture was presented with an animation of blue lights moving from both ends of the LED strip to the centre. The entire animation lasted for 500 ms. V-off feedback was an outward animation of red lights (from centre to the ends of the LED strip). Red and blue colours were chosen to avoid issues for users who were colour blind. This animation was inspired by how conductors inform the orchestra to start or end the music. Feedback for SL and SR gestures mimicked their movements with animations moving from right to left, and left to right respectively. The design was inspired by the *Do that, there* system [34] where Peripheral Lights moved from side to side mimicking the gesturing hand. Duration of the entire animation was 350 ms and with each motion, the colours transitioned from red to blue or blue to red, respectively. Feedback for the CW and ACW gestures were 500 ms long pulses of the entire strip. The colours transitioned from blue to red with a clockwise motion and from red to blue with a anticlockwise motion, based on the setup in [51].

Sensor Strength Feedback

Users need to know where to gesture, so that they interact where their hand movements can be detected by a gesture-sensing system. Gestures performed outside of a system's sensor range cannot be detected and gestures executed at the limits of this range might not be detected reliably [51]. The system therefore, needs to inform the user, where to gesture for optimal recognition. Especially in a driving situation, this feedback needs to be informative but not distracting.

In this study, sensor strength information was displayed to a fist gesture to avoid unintentional feedback. The fist gesture has been used by Sterkenburg *et al.* [108] to navigate in an interaction space (Section sec:attention). The participant formed a fist, and entered the hand into the gesture sensing area. Then participants received modality dependent feedback to adjust the position of their fist to be in the "sweet spot" of the interaction box (Figure 2.10). Positioning the hand in the "sweet spot" allows users to complete gestures *within* the vision of the sensor. A circle gesture, for instance, is only recognised if the entire motion was executed within the sensor's range of vision. Once the fist is opened to a flat hand, sensor strength feedback ceased.

Following the *Proxemic Flow* [105] design, sensor strength feedback for Visual and Peripheral Lights was colour coded according to a traffic light system. If the participant's fist was in the centre of interaction area, the LED strip flashed a dim green colour; it transitioned to red the further the hand moved away from the "sweet spot". For Visual feedback, a colour-coded dot of 1 cm diameter mapped the position of the driver's hand onto the centre console screen screen. If the fist was outside the sensing area, no feedback was provided. Sensor strength feedback for the Auditory and Cutaneous Push conditions were designed in the fashion of a Geiger counter, with increasing feedback frequency, the closer the fist moved to the centre. Pin L3 provided the tactile Geiger counter feedback, and the note c5 was presented for the auditory Geiger counter feedback.

4.3.3 Apparatus

The experiment took place in a usability laboratory equipped with a computer, on which the OpenDS simulation was run, a 24 inch screen on which the driving simulator was displayed, an 8 inch screen to the right of the driver mimicking a car's centre console screen, a Leap Motion tracker to sense the user's gesturing hand, a Logitech web camera located on top of the main screen, three solenoid powered pins protruding from the steering wheel providing feedback to the driver's left palm [20], a capacitive sensor attached to the steering wheel under the driver's right hand (to measure hands-off-the-wheel time), and a 107 cm long Adafruit NeoPixel LED light strip [232] (Figure 4.3). The placements of the individual devices were guided by the measurements of a Jaguar Land Rover Discovery Sport. The Leap Motion device was placed where the gear stick would be such that the interaction area is a cube on the right of the steering wheel, above the gear stick. This ensured that the gesture execution area was close to the steering wheel, as recommended by Riener *et al.* [2]. The measurements of the interaction box are the Leap Motion's default settings: width: 235.24 mm, height: 235.24 mm, and depth: 147.75 mm.

The webcam recorded the participants' eye gaze while performing the driving and input tasks. Eye gaze direction analysis showed the amount of eyes-off-the-road time caused by the interaction. Gaze and head pose data were extracted using OpenFace [233], an open source tool for eye-gaze and head pose estimation. An SVM classifier with a linear kernel was trained on 7078 images obtained during a pilot study. Input data for the classifier were 3D vectors for each eye and head pose rotation. The SVM model classified 91.54% eyes-off-the-road time correctly (10-fold cross validation).

OpenDS Version 3 [213] was used to simulate a lane-keeping driving scenario. Participants had to drive the car in the middle lane. The centre of the motorway (middle of middle lane) was used as the zero point for measuring lane deviation. Bridge panels above the motorway reminded the driver throughout the study, to stay in the middle lane (Figure 4.3).

4.3.4 Measures

The Independent Variable was feedback type. There were four levels: Visual, Auditory, haptic and Peripheral Visual. The Dependent Variables were: lane deviation (metres), visual attention to primary task (number of glances at centre console, average duration per glance in ms, average time between glances in ms), number of correct of gestures (% correct), task duration (hand-off-the-wheel-time in ms), perceived workload (NASA TLX), and a questionnaire (demographics, handedness, preferences of feedback).

As mentioned in the Literature Review (Section 2.2), cognitive workload can be measured through pupil dilation, however it is not a standard in the driving community. Further, the technology to accomplish this was not available for this project, due to financial constraints. Longitudinal data (i.e. speed variability) was not measured as it is not a commonly used protocol because it adds mental demand on the driver [49].

4.3.5 Hypotheses

- **H1:** Visual distraction from the primary driving task will be significantly decreased in the non-visual conditions;
- **H2:** There will be a significant difference in lane deviation across the conditions, with lane deviation highest in the Visual feedback condition;
- **H3:** Gesturing success will be significantly higher in the Visual feedback condition;
- **H4:** There will be a significant difference in perceived workload across the conditions, with Visual having the highest;
- **H5:** Users will prefer the non-visual feedback types over the Visual feedback.

Hypothesis **H1** predicts that eyes-off-the-road time (EORT) will be significantly less during the non-visual feedback conditions than during the Visual condition. As discussed in the Literature Review, a large body of research has shown that non-visual infotainment feedback reduces EORT significantly. Consequently, hypothesis **H2** predicts deterioration of driving performance due to increased visual distractions in the Visual condition. The more often and the longer the eyes are off the road, the higher the risk for poor driving performance and increased crash risks [58]. Hypothesis **H4** expects differences in workload between the feedback conditions. As discussed previously (Section 2.2), increased glances off the road correlate with higher workload and impact perceived driving safety of participants [69]. Therefore, hypothesis **H5** predicts that Visual feedback will be the least preferred technique.

Hypothesis **H3** argues that gesturing performance will be higher during Visual feedback. The reasoning for this is that participants are generally more accustomed to Visual feedback from the centre console in cars than other feedback types.

Pilot Study

As mentioned before, it is important for the user to know *where* to gesture. During the pilot study, sensor strength feedback was presented to the fist gesture. However, it proved to be unnecessary to display sensor strength feedback in a small interaction area such as the car cockpit. The driver's torso is in immediate proximity to the gesture sensing area, and initial observations showed that after a few preliminary executions, muscle memory sufficed to locate the "sweet spot".

Participants were introduced to the gesture sensing area through Leap motion's demo view (Figure 4.5). This view provides users with the knowledge about the size of the sensing area, the location of the sensor's centre, and the reliability of the gesture recognition. The introduction to the study via Leap motion's demo view provided participants with the necessary knowledge about *where* to gesture.

4.3.6 Procedure

On arrival, participants were provided with an introduction to the experiment. This included two executions of each mid-air gesture in every condition (4 gestures per condition x 2 executions per condition and x 4 feedback modalities = 32 gesture executions). After approximately 20 seconds of stabilised driving in the middle lane, the experiment and recordings of the data started. The experiment consisted of four blocks, one block for each feedback condition. During each block, participants executed 30 mid-air gestures (10 x SL/SR, 10 x V, 10 x CW/ACW). Each block lasted approximately 10 minutes. To counterbalance for any learning effect, the conditions were ordered via a Balanced Latin Square.

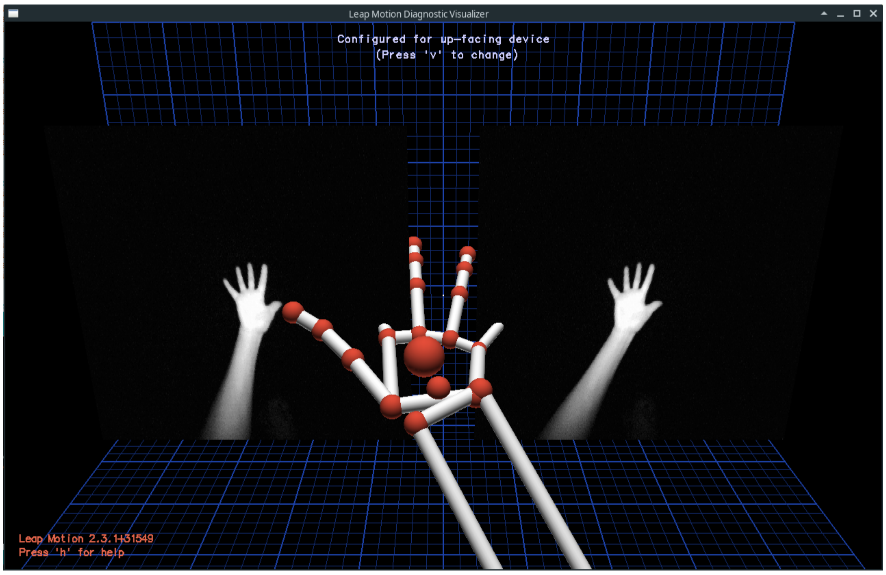


Figure 4.5: Leap Motion's diagnostic visualiser. It shows the user the infrared images captured by the device (i.e. what the device "sees"). In a three dimensional grid (the interaction box), the gesturing hand is projected. In the centre of the box, there is a small dot, indicating the sensor's sweet spot.

Mid-air gesture instructions were presented via a pop-up message box at the centre top of the main screen above the road. The instructions were also provided via speech through headphones the participants were wearing at all times. The message box was displayed for 3 seconds and the accompanying auditory instructions lasted up to 2 seconds. The auditory instructions were "swipe left/right 2-4", "(anti) clockwise 2-4", "victory" (and during the introduction phase there was an additional "find sweet spot"). The speech instructions were read aloud by a male US American voice (www.cereproc.com/ Voice: Nathan. Accessed 2016-01-31). This reduced the chances of participants missing an instruction.

Once an instruction to gesture was provided, the participants took their right hand off the wheel (whilst steering the simulated car with their left), executed the requested gestures as fast and as accurately as possible, and returned the hand back to the steering wheel. Once the hand was placed back, there was a random interval of 5 - 10 seconds before the next gesture execution. This interval provided an opportunity to return the car to the middle lane and regain stabilised driving, if necessary. After each feedback condition block, participants were asked to fill in a NASA TLX workload questionnaire.

4.3.7 Participants

Nineteen participants (10 females) ranging from 19 to 35 years of age (μ 24.42 σ 5.79) were recruited via the University of Glasgow's student online forum. Of these 19, nine participants had a Left-Hand-Traffic (LHT) driving license and 10 a Right-Hand-Traffic (RHT) driving

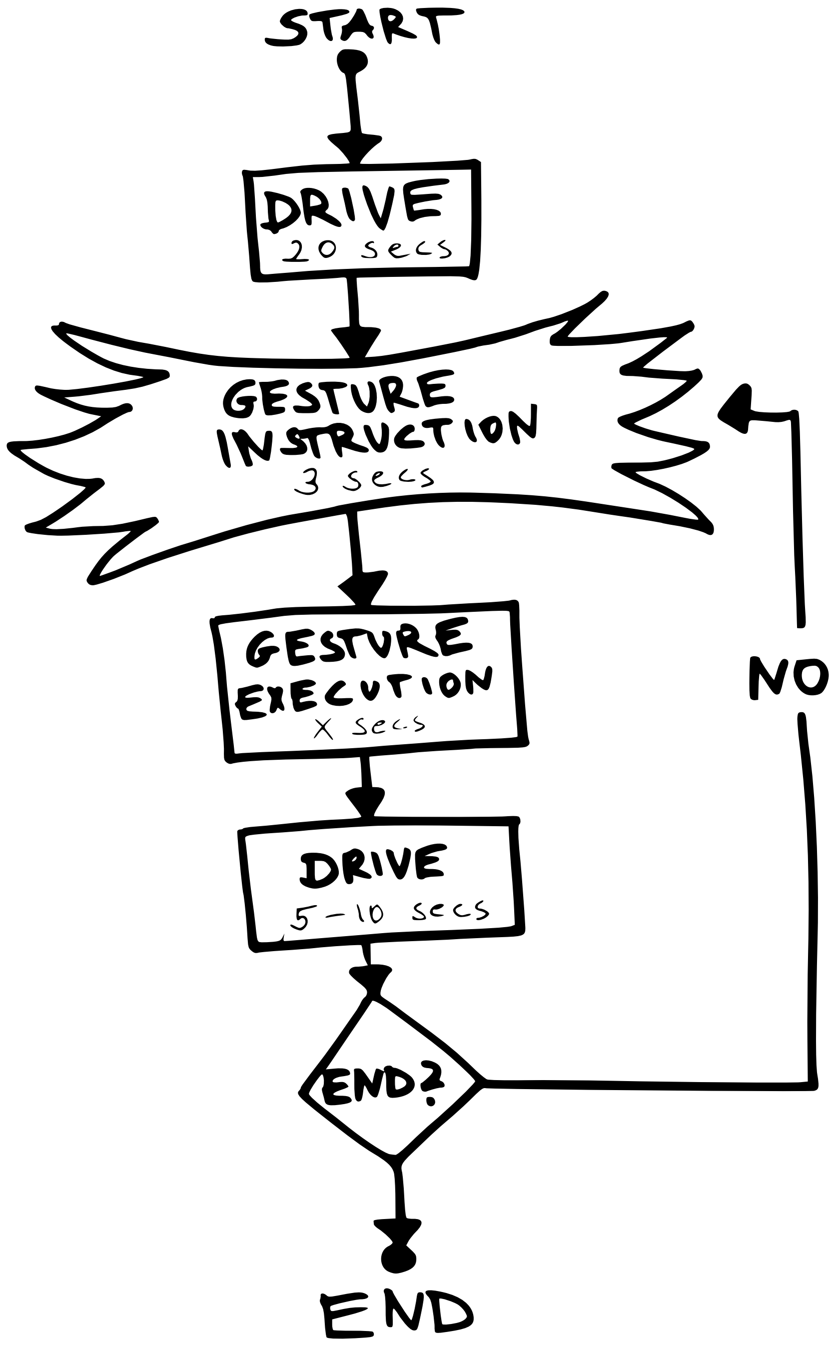


Figure 4.6: Flow chart of a block. A block consists of: participant drives for 20 seconds straight, a gesture instruction is given via pop-up box and auditory instructions for 3 seconds, the participant executes the requested gesture as fast and as accurately as possible, and continues driving for 5-10 seconds. If it was the last trial of the block, the simulation stops.

license. A total of 13 participants indicated that they had no prior experience with mid-air gesture interfaces. Two participants were left handed. Participants were paid £6 for an hour of their time.

4.4 Results

4.4.1 Gaze Behaviour

Shapiro-Wilk normality test showed that eye gaze data was non-normal ($W = 0.411, p - value < 0.001$). An ANOVA analysis of Aligned Rank Transformed (ART) [234] data was executed on whether gesture or feedback type can predict eyes-off-the-road time. The results show, that looking away time is significantly influenced by feedback type ($chi^2(3) = 70.771, p < 0.001$) and by individual gestures ($chi^2(12) = 8.198, p < 0.001$). Visual feedback caused significantly higher EORT than Auditory ($p < 0.001$), Peripheral Lights ($p < 0.001$), or Cutaneous Push ($p < 0.001$) feedback. An ART ANOVA showed that gesture type (CW, SL, V, etc) influences EORT significantly ($chi^2(4) = 25.794, p < 0.001$). A pairwise multiple comparison test showed that all gestures, as well as gesture types had a significant impact on EORT compared to Victory, with CW ($p < 0.001$), ACW ($p < 0.001$), SL ($p < 0.001$), and SR ($p < 0.001$) increasing EORT.

4.4.2 Driving Performance

Driving performance was measured in the same fashion as in the first three experiments. Driving data was non-normally distributed $W = 0.411, p < 0.001$, as shown by Shapiro-Wilk normality tests. An ART repeated measures ANOVA showed that there is a significant impact of gesture ($\chi^2(12) = 6.886, p < 0.001$) and condition ($\chi^2(3) = 6.418, p < 0.001$) on driving behaviour; however, not the combination of both ($\chi^2(36) = 1.204, p = 0.193$). A pairwise multiple comparison test showed that Visual ($p = 0.001$) and Peripheral Lights ($p = 0.002$) feedback significantly increased lane deviation compared to Auditory feedback (Figure 4.7). Further pairwise multiple comparison *post hoc* test showed, that Victory gesture had a significantly lower impact on lane deviation than CW3 ($p = 0.029$), CW4 ($p = 0.031$), ACW4 ($p = 0.034$), SL3 ($p < 0.001$), SL4 ($p < 0.001$), SR2 ($p = 0.012$), SR3 ($p < 0.001$), and SR4 ($p < 0.001$). Further, CW2, ACW2, and ACW3 had significantly less impact on driving than SL3 (CW2: $p = 0.034$, ACW3: $p = 0.089$), SL4 (CW2: $p < 0.001$, ACW2: $p = 0.005$, ACW3: $p = 0.001$), SR3 (CW2: $p = 0.001$, ACW2: $p = 0.017$, ACW3: $p = 0.004$), SR4 (CW2: $p = 0.008$, ACW3: $p = 0.026$).

Figure 4.7: Feedback conditions plotted according to lane deviation and Eyes-Off-the-Road time.

An ART ANOVA was run on whether gesture type influences driving behaviour, with a significant result ($\chi^2(4) = 24.638, p < 0.001$). *Post-hoc* multi comparison test of mean values showed that there is a significant difference between all gestures types except CW and ACW ($p = 0.999$), and SL and SR ($p = 0.996$).

4.4.3 Gesturing Performance

The gesture performance data was binary since the participants either correctly or incorrectly executed the gesture instruction. Overall gesture performance was 69.06%. Success rates for gestures differed significantly ($z = 2.822, p = 0.035$) between the gesture families, with CW 69.01%, ACW 76.53%, SL 59.21%, SR 44.27%, and V 96.26%.

A binomial regression was run on whether feedback type influenced gesturing performance. Feedback type significantly impacts gesturing outcome ($z = 5.265, p < 0.001$). Multiple comparisons of means showed that there is a significant difference in performance between Visual and Peripheral ($z = -2.869, p = 0.021$), and Visual and Cutaneous Push ($z = -5.164, p < 0.001$), as well as Auditory and Cutaneous Push feedback ($z = -4.604, p <$

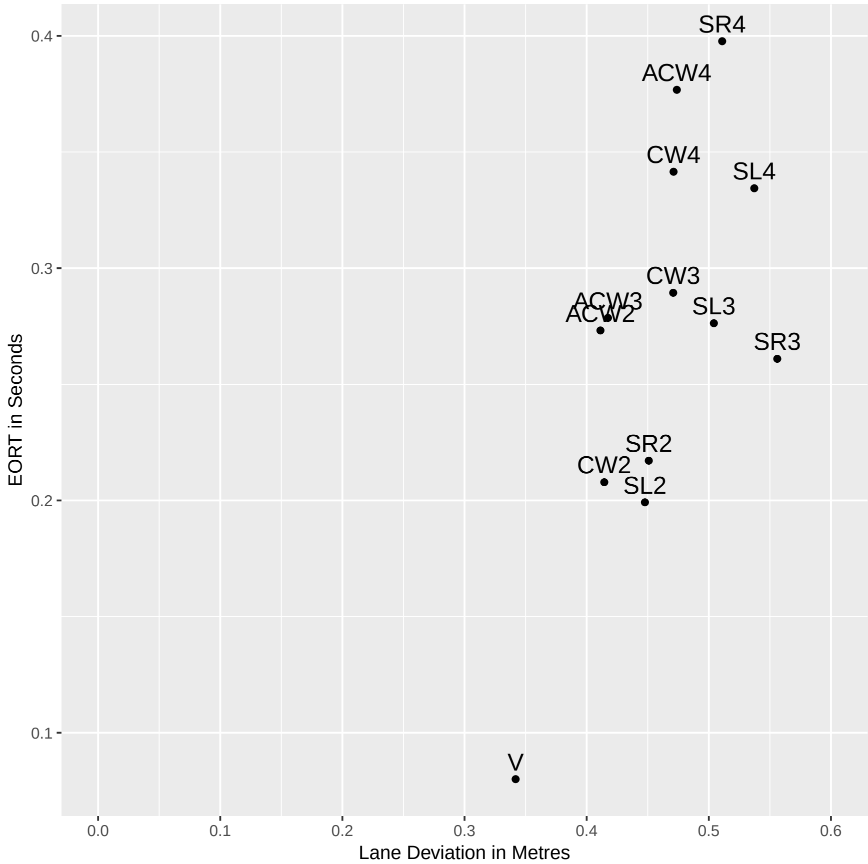


Figure 4.8: Impact of gestures on lane deviation and EORT. Gestures: Circle Clockwise 2, 3, 4 times (CW2, CW3, CW4), and Circle Anticlockwise 2, 3, 4 times (ACW2, ACW3, ACW4), Victory (V), Swipe Left 2, 3, 4 times (SL2, SL3, SL4), and Swipe Right 2, 3, 4 times (SR2, SR3, SR4).

0.001). Average performance rates for each feedback type are Visual with 74.56%, Auditory with 73.14%, Peripheral Lights with 67.36%, and Cutaneous Push with 61.22% (Figure 4.10).

Hands-off-the-Wheel (HoW) duration was non-normal ($W = 0.905, p < 0.001$). A repeated two-way ANOVA on aligned rank transformed HoW data showed, that condition significantly influences HoW duration ($\chi^2(3) = 4.461, p = 0.004$), as well as gesture family ($\chi^2(4) = 94.107, p < 0.001$); however, there is no mixed effect of both on HoW ($\chi^2(12) = 0.871, p = 0.576$). Post-hoc multiple comparison showed a difference between Peripheral and Visual ($p = 0.031$), and Peripheral and Cutaneous Push ($p = 0.027$), with P impacting HoW duration the most. Post-hoc multiple comparison showed that Victory gesture impacts HoW duration the least ($p < 0.001$). Spearman's rank test was run to determine whether there is a correlation between HoW time and successful gesture execution. No significance was found ($S = 243, \rho = 0.169, p = 0.408$).

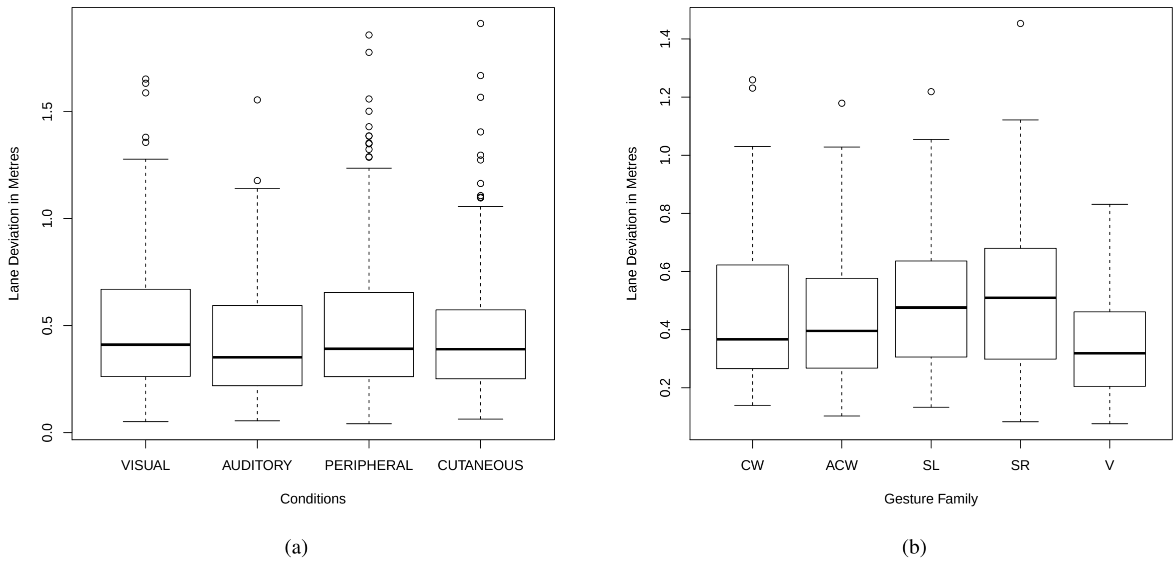


Figure 4.9: Impact of feedback conditions (left) and gestures families (right) on lane deviation. Gestures: ACW: Anti-clockwise, CW: Clockwise, SL: Swipe Left, SR: Swipe Right, V: Victory.

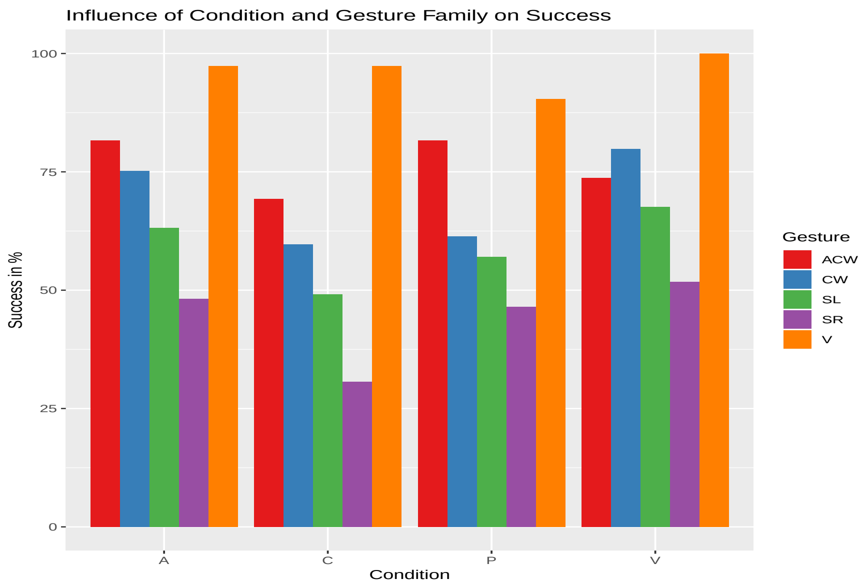
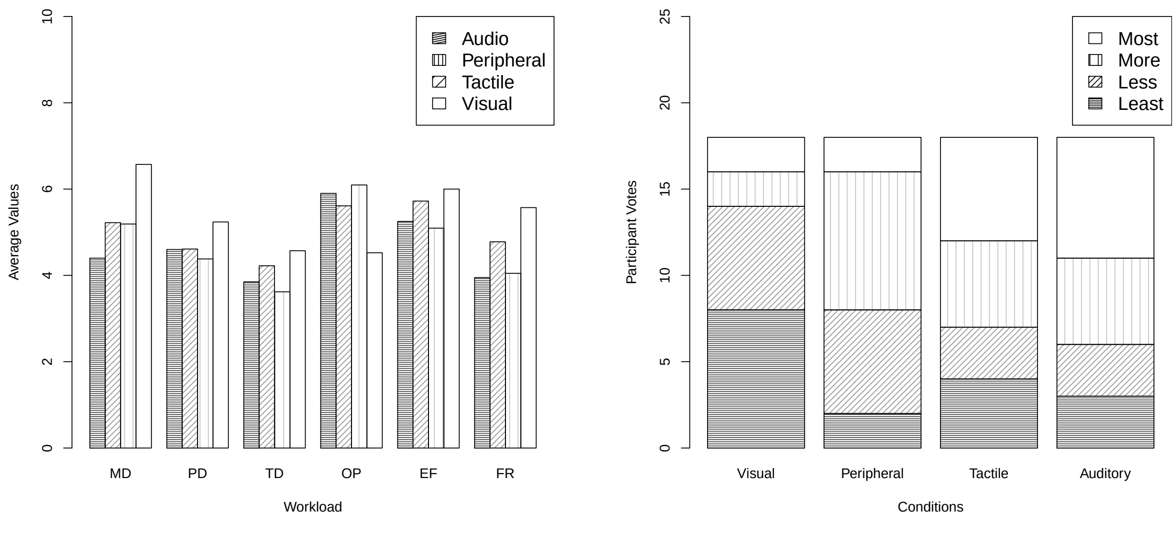


Figure 4.10: Gesture performance presented across feedback type and gesture family. Conditions: A: Auditory, P: Peripheral Lights, C: Cutaneous, V: Visual. Gestures: ACW: Anti-clockwise, CW: Clockwise, SL: Swipe Left, SR: Swipe Right, V: Victory.

4.4.4 Qualitative Data

MANOVA test of the NASA TLX questionnaire revealed a significant difference in mental demand ($\chi^2(3) = 2.9153, p = 0.04$), with Cutaneous Push feedback having the highest level (Figure 4.11), and in perceived performance ($\chi^2(3) = 3.801, p = 0.012$). Visual feedback negatively impacted mental demand and perceived performance significantly. There were no significant differences in the remaining measures: physical demand ($\chi^2(3) = 0.707, p = 0.551$), temporal demand ($\chi^2(3) = 1.036, p = 0.381$), effort ($\chi^2(3) = 0.887, p = 0.451$), and frustration ($\chi^2(3) = 2.313, p = 0.082$).



(a) (b)

Figure 4.11: Left: NASA TLX questionnaire results displaying users rating of perceived demands. 0 is low demand and 10 is high demand. Right: User preferences of the feedback modalities. MD: Mental Demand, PD: Physical Demand, TD: Temporal Demand, PE: Performance, EF: Effort, FR: Frustration.

Each participant ranked the feedback types from most to least preferred. Analysis of the questionnaire showed that 38.9% of participants preferred Auditory feedback, followed by 33.3% preferring both Peripheral Lights and Cutaneous Push feedback. Visual feedback was ranked as least preferred feedback type by 44.4% of the participants.

4.5 Discussion

In this chapter, the effects of four different types of feedback on mid-air gesture interaction during simulated driving were investigated. The results provide insights into the effects of feedback type on the primary driving task and the secondary gesturing task.

> **H1** Visual distraction from the primary driving task will be significantly decreased in the non-visual conditions

The results suggest that providing non-visual feedback for mid-air gesture input is promising since it reduces Eyes-off-the-Road Time significantly (Figure 4.7), with Auditory and

Cutaneous Push feedback resulting in the least time looking away from the road. Therefore, hypothesis **H1** was accepted.

> **H2** There will be a significant difference in lane deviation across the conditions, with lane deviation highest in the Visual feedback condition

Hypothesis **H2** was also accepted since feedback type influenced driving performance significantly, with Visual and Peripheral Lights feedback having the most negative influence.

> **H3** Gesturing success will be significantly higher in the Visual feedback condition

Hypothesis **H3** is accepted since there was a significant difference between secondary task performance depending on feedback condition. Gestures were performed best during the VF condition (Figure 4.10). The reason behind this high performance rate during VF is due to participants being familiar with visual feedback in general. However, it is important to notice, that participants were provided system state in the Visual condition. The scale on the centre console screen provided numbers where participants could keep track of the success of their interaction. None of the other feedback modalities provided system state, which is a design limitation. During the other conditions, it is assumed that participants needed to count the number of correctly executed gestures in addition to executing them. Gesture performance during AF was second highest, which is in accordance with the literature suggesting that Auditory feedback is a suitable alternative for visual feedback. Cutaneous Push feedback did not support gesture interaction as well as the other techniques.

Analysis of type of gesture revealed that gestures which require more time to execute (e.g. ACW4), influenced eyes-off-the-road time significantly across all conditions. The more time the gesture required for execution, the greater the glance duration and number of glances off the road. Further, the longer a gesture required for execution, the less successful it was. The wider the time window for gesture operation, the more units of movement are executed, and the more mistakes can be made. In other words, the longer the duration, the more consistently accurate the movement has to be. A long term effect of mid-air gesture execution might be fatigue of the arm and shoulder since participants had to move their entire arms [235]. This means that in-car mid-air gestures should be designed such that they require little arm and shoulder movements and are short, such as the V gesture.

Further analysis revealed a significant difference in secondary task performance across gestures. The V gesture yielded the highest performance accuracy with 96.26%. This might be due to the V gesture consisting of a single discrete and static motion. Other gestures consisted of two or more motions (e.g. SL2, CW2). Swipe motions performed worst, especially

SR. CW motions performed worse than ACW gestures. This might be due to the SR and CW gestures being motions where the arm is moving away from the torso of the driver. This “away” movement might have caused greater arm and shoulder fatigue [235]. The difference between the circular motion and the swipe motion was the nature of their continuity. A CW2 motion is one continuously performed gesture. With SL2, the user has to return the hand to the start point and swipe again. This interruption of rhythm — the new alignment of the hand inside the interaction box — might have caused the different performance rates between the gestures.

> **H4** There will a significant difference in perceived workload across the conditions, with Visual having the highest

There was a significant difference in perceived mental demand across the conditions, thus **H4** was accepted. Visual feedback caused highest perceived mental demand and lowest perceived performance, despite quantitative analysis showing that gesturing performance was highest in Visual feedback. However, this difference in cognitive workload was expected as Liang *et al.* [58] have shown a correlation between glances off the road and mental demand. Visual distractions lead to higher perceived cognitive workload [140], especially if secondary tasks are complex and require a number of steps to achieve the end goal [69]. This was confirmed by participants P18 with “the position of the small screen felt a bit too far from the PC screen”. The physical setup - which was informed by a Jaguar Land Rover Discovery Sport - lead to an increased number of head movements towards the centre console screen. This is reflected in the increased Physical Demand result during the Visual feedback conditions.

> **H5** Users will prefer the non-visual feedback types over the Visual feedback

Generally, non-visual feedback increased subjective impression of safe driving, which was reflected in Visual feedback being ranked least preferred and Auditory feedback most preferred. Second most preferred feedback modality was Cutaneous Push, despite participants experiencing difficulties due to unfamiliarity with the feedback mechanism which was expressed as “it was not as easy to differentiate between the different swipe types than the others [feedback types]”. Therefore, hypothesis **H5** was accepted since VF was ranked least preferred. AF was ranked most preferred followed by CPF.

Interestingly, RHT participants had significantly better gesture performance than LHT participants, 76.75% and 60.5% respectively, even though all were right handed but one person per group. Since there was no impact of LHT versus RHT on driving behaviour, a possible conclusion is that LHT participants are not used to operate an in-car interaction system with their right hand and maintain stable driving with their left hand. Therefore, they prioritised safe driving over correct gesture performance.

4.5.1 Limitations

This study investigated four modalities for mid-air gesture feedback in driving scenarios. The design choices in the presented study only allowed feedback to an expected gesture. Thus, the results are a best case scenario as eyes-off-the-road time can increase in the case of error states. However, this study investigated the impact of feedback; it did not aim to create the perfect gesture sensor system.

The feedback was designed such that it did not provide any system state, except during the Visual condition. During each other condition, users received feedback from the system about successful gesture execution, but no additional meaning to it. For example, if the participants were instructed to circle clockwise three times during the Peripheral Lights condition, the entire LED strip flashed after each successful execution. However, it might have been more informative, if with each successful gesture execution, one specific segment of the LED had lit up. An increase of blue light segments towards the right could indicate a rise (of some value e.g. temperature), and a movement of the light segments to the left could indicate a decrease (similar to the scale in the Visual condition).

As discussed in Section 2.4, mid-air gesture interaction benefits from *Attention* feedback, especially in a driving environment. A lack of feedback can encourage the driver to take their eyes off the road in an attempt to understand the current problem. If the systems does not show system attention, then users do not know whether the lack of response to their input was due to their movements not being sensed, or if they were sensed but their input not recognised as a valid gesture. Attention feedback will be provided in the next iteration.

Swipe motions performed worst, especially SR. SR gestures are motions where the arm is moving away from the torso of the driver and this “away” movement might have caused greater arm and shoulder fatigue [235]. The difference between the circular motion and the swipe motion was the nature of their continuity. A CW2 motion is one continuously performed gesture. With SL2, the user has to return the hand to the start point and swipe again. This interruption of rhythm — the new alignment of the hand inside the interaction box — might have caused the different performance rates between the gestures. Further, “resetting” the swiping motion — returning the hand to the starting point to swipe again — might have caused misclassification of the intent. The user wanted to swipe right again, thus brought the hand back to the left and this “resetting” was interpreted by the Leap Motion device as a left swipe.

The chosen interaction box size was too large for the car cockpit setup. Occasionally, the sensing system classified the resting hand on the steering wheel as a Fist gesture and provided sensor strength feedback. This will be mitigated in the next iteration. The size of the interaction box might have also obstructed successful execution of swiping gestures. To allow drivers to swipe in a car cockpit, the interaction area has to be of appropriate size. On the

	EORT	Lane Dev	Gesture	Workload	User Preference
Visual	X	X	✓	X	X
Auditory	✓	✓	✓	✓	✓
Peripheral Lights	✓	X	X	✓	✓
Cutaneous Push	✓	✓	X	✓	✓

Table 4.3: Significant impact ("X") of the feedback types on EORT, driving and gesturing performance, mental workload and user preference. Visual feedback had a significant impact on all measures but gesture performance. Peripheral lights feedback negatively impacted driving and gesturing performance. Cutaneous Push impacted gesturing performance negatively. The results suggest that Visual feedback for mid-air gestures impacts all aspects of driving negatively.

one hand, the size of the interaction box, has to be small enough to allow for "reset" motions outside the box; on the other hand, it needs to be large enough to allow for space to gesture. The new dimensions of the interaction box will be guided by research findings.

Finally, despite its inherently non-visual information presentation, non-visual feedback still resulted in some EORT. As study observations showed, a large portion of off-road glances might have been caused by the (at times undependable) gesture recognition of the Leap Motion device. It mis-classified gestures which led to elongated gesturing time, elongated hands-off-the-wheel time, and caused frustration with the participants, which occasionally led them to abandon execution of the requested gesture instruction.

4.6 Conclusions

This chapter presented an investigation into the effects of different feedback modalities on mid-air gesture interaction in cars. A simulated driving study was conducted to investigate how different types of unimodal feedback can support in-air gestures.

The non-visual feedback techniques tested in this study caused least distraction from the road. As discussed throughout this thesis, it is important to keep visual distraction limited to avoid increasing risks of crashes. Auditory, Peripheral Lights, and Cutaneous Push feedback were shown to cause least eyes-off-the-road time, and Visual feedback the most (Table 4.3). It is alarming to notice that the most commonly used feedback technology — Visual feedback via centre console — causes the most EORT, highest mental demand, and highest frustration. It further caused greater physical distraction due to head movements towards the centre console. Visual feedback significantly increased all aspects of driver distraction: visual, cognitive, and manual distraction [57].

Non-visual feedback techniques investigated in this study show promise for in-car usage. The results presented in Table 4.3 suggest that Auditory feedback is the most appropriate feedback technique for mid-air gesturing in cars. However, Auditory feedback can be interrupting in conversations or when listening to music, and it is not always a discreet message delivery system. A multimodal combination of the feedback techniques presented here could be a promising solution to harnessing each technique's strengths. For instance, Freeman *et al.* [34] showed that Peripheral Lights in combination with tactile feedback can successfully overcome the shortcomings of each feedback type and provide an additional modality for mid-air gesture feedback. A plethora of research has shown, that delivery of information to multiple sensory channels provides redundant information, which alleviates mental effort without negative impact, particularly in driving scenarios.

The findings from this study also showed that gesture sensing systems need to be more reliable in order to avoid additional cognitive demands [236]. False positive gesture recognition, e.g. recognition of a gesture, the user did not intentionally direct towards the sensing system, can confuse them and increase distraction as mental resources are redirected from driving towards the understanding of the new system state. False negatives, e.g. the system analyses movements in sequence and recognises two swipes where only one was executed, also increases cognitive demands and frustration. It is important for gesture sensing systems to reliably recognise gestures (i.e. avoid gesture accidents, as discussed in Section 2.4.5) if they are to be incorporated into driving situations. However, as gesture sensing systems are not reliable enough yet, feedback can inform the user exactly what they have just done or are in the process of doing, so that they remain mentally ordered and in control of the interaction [104]. However, feedback designers should avoid overly attention grabbing qualities in error messages, as well as negative qualities as negative driver affect has been shown to impact driving performance [127].

4.6.1 Research Question 2

It is important to provide feedback to the gesturing driver to keep them informed about the outcome of their interaction. However, the feedback should not be cognitively demanding, nor impact driving or gesturing behaviour. This study's findings suggest that non-visual feedback for mid-air gestures is a valid alternative for centre console feedback in driving situations. The outcomes of the experiment are now summarised as recommendations in response to the following research question:

> **RQ2:** How do *unimodal* mid-air gesture feedback techniques influence driving performance and in-car interaction (*Experiment 4*)?

Drivers need feedback from gesture sensing systems to align their mental model of system state with the actual system state. Discrete system state feedback *after* gesture execution can support the driver during interaction, as it informs them about whether the command was executed/interpreted successfully.

Generally, discrete gestures such as the Victory gesture should be utilised in a limited area such as a car cockpit compared to continuous gestures such as swiping and circling. Discrete gestures can be executed more quickly than continuous gestures, as well as more successfully.

4.6.2 Contributions

The research in this chapter makes the following contributions:

- It presents two novel feedback techniques for in-car mid-air gestures, namely Peripheral Lights and Cutaneous Push feedback;
- It investigates the impact of unimodal feedback for mid-air gesture interaction in simulated driving environments;
- It finds that participants prefer Auditory feedback over Peripheral Lights and Cutaneous Push, and particularly over Visual feedback.

Chapter 5

Multimodal Feedback for Mid-air Gestures in Cars

5.1 Introduction

Multimodal information displays can be beneficial as information is distributed across multiple sensory modalities [42, 43, 44, 45, 14, 46, 47, 48]. This is especially important for drivers, as driving is a cognitively demanding task [42, 43, 44, 31]. By offloading feedback to other sensory modalities, a reduction of the demands of in-car interaction is achievable [41]. Chapter 4 started to explore the use of non-visual feedback for in-car gestures. It found that auditory cues and haptic feedback from the steering wheel allowed drivers to keep their eyes on the road, although since feedback was given in a single modality, feedback content was limited. The limited amount of information was not as effective in supporting gesture interaction as visual feedback shown on the console screen, which required eyes off the road.

This chapter builds on these and previous findings by further investigating non-visual feedback for mid-air gestures. The key aim of this chapter is to investigate the appropriate use of bimodal feedback to exploit the possibility of redundant information, such that it will not decrease driving performance and not increase user workload. This chapter aims at answering the following Research Question:

> **RQ3:** How do *multimodal* mid-air gesture feedback techniques influence driving performance and in-car interaction (*Experiments 5, 6, & 7*)?

This chapter describes three experiments which investigate the effects of bimodal feedback on driving performance, visual attention, secondary task performance, and driver workload. Study 5 looks at five bimodal feedback combinations: Auditory-Visual, the baseline which is representative of typical in-car systems; Tactile-Visual (Cutaneous Push feedback from the steering wheel and centre console feedback); Auditory-Tactile; Auditory-Peripheral (peripheral lights from an LED strip); and Tactile-Peripheral. The latter three feedback types use non-visual and/or peripheral vision to enable drivers to focus on the road. The feedback types used in this chapter are refined versions of the feedback design from Study 4. In a simulated driving experiment, the efficacy of these feedback combinations were tested.

Study 6 investigates bimodal feedback where users performed mid-air gestures whilst performing a Lane Change Task (LCT). This is a standard task (ISO standard 26022:2010) used in automotive studies to investigate the demands of secondary tasks whilst driving (e.g., responding to navigation instructions or interacting with a system). Study 6 evaluated the use of the same bimodal feedback techniques as in Study 5, but Tactile-Visual. Tactile-Visual feedback resulted in highest EORT and lane deviation, as well as lowest user approval; thus it was omitted from further investigation.

Study 7 introduces ultrasound for mid-air gesture interaction since car manufacturers like BMW (HoloActive Touch [237]) and Bosch (neoSense [238]) are using it in their next generation cars. However, the impact of this feedback technique for mid-air gestures has not yet been investigated. There is a necessity to understand and mitigate the effects of ultrasound feedback for mid-air gestures such that neither driving performance nor safety is negatively impacted by increased workload or distraction of the driver [22, 62]. Study 7 investigates ultrasound feedback unimodally as well as bimodally combined with Visual, Auditory, and Periperal Lights feedback. Therefore, the contribution of Study 7 is multimodal ultrasound feedback and its effect on driving performance, visual attention, and perceived mental demand during the Lane Change Task.

The contribution of Studies 5 - 7 are a detailed investigation of the effects of multimodal mid-air gesture feedback whilst driving. The latter two studies also look at the impact of bimodal gesture feedback during more challenging driving (i.e. LCT) and therefore contribute to the following Research Question:

> **RQ4:** What effect does multimodal mid-air gesture feedback have on interaction in more *challenging driving* (*Study 6 & 7*)?

These three studies investigate multimodal feedback for gesturing, because feedback is essential for in-car gesture interaction [38]. It is a core part of providing a 1) sense of agency to the gesturing driver [35], 2) reducing eyes-off-the-road time [31, 166], and 3) distributing secondary task information to a non-visual channel. By offloading interaction feedback to multiple modalities, the demands of interacting with the in-car systems are decreased and the noticeability of the feedback increased. Findings from the experiments presented in this chapter make a contribution to improving gesture interaction in driving scenarios.

5.1.1 Chapter Structure

Section 5.2 describes the design of the multimodal feedback for gesture interaction (Study 5). Section 5.3 presents Study 6 which builds on the findings of the multimodal feedback techniques, and adds more challenging driving via the Lane Change Task, to assess demands of the secondary gesturing task. Study 7 (Section 5.4) expands the findings by investigating ultrasound feedback during the LCT. Section 5.5 gives conclusions and revisits the research question discussed earlier in this chapter.

5.2 Study 5: Bimodal Mid-air Gesture Feedback

The study presented in this section introduces bimodal feedback for mid-air gesturing in cars. The feedback techniques used for multimodal combinations were presented in Chapter 4; however, results from the previous study informed two changes to each feedback. Firstly, whenever the hand entered the gesture interaction area, *Attention* feedback was given to assure the user that the system was attentive and ready for input [104, 50, 239]. There was no feedback provided on the hand exiting the interaction box.

Secondly, system state was displayed in each modality. It is important to inform the user about the new state of the system to keep additional demands to a minimum. Feedback about the system state aligns the user's mental model with the current state.

Another three changes were made to the physical layout of the laboratory (Figure 5.1), informed by Study 4. Firstly, the size of the interaction box was minimised to reduce accidental gesture input; and to allow users to "reset" their gestures comfortably outside of the gesture sensing area. Secondly, instead of using a 27 inch screen like in the previous setup, a Dell projector displayed the driving simulator as an 80 inch large projection on the wall in front of the participant. This was done to increase the fidelity of the simulation. Finally, blackout blinds were installed to guarantee consistent lighting in the laboratory for optimal projection.

5.2.1 Research Aims

The study presented in this section introduces bimodal feedback for mid-air gesturing in cars. A simulated driving study was designed to evaluate the effectiveness of different bimodal feedback techniques for three different mid-air gestures. The aim was to gain insight into the modality combination which best supported interaction without compromising driving performance.

Similar to Study 4, the first aim was to investigate the impact of feedback on driving performance. This includes the impact on deviation from the optimal path, visual distraction,

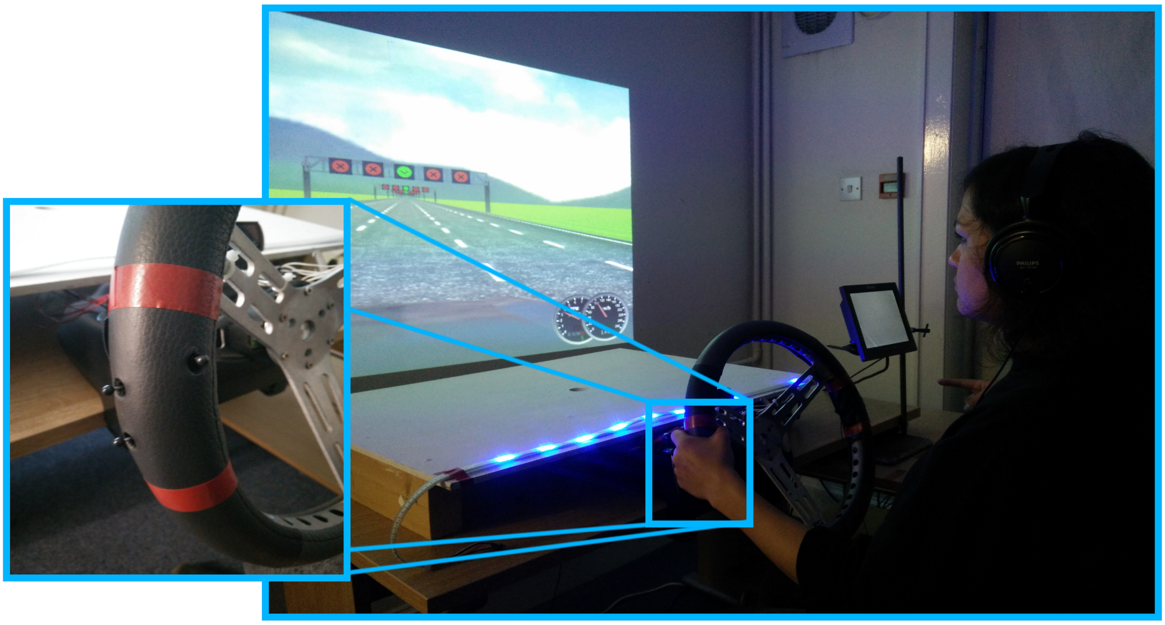


Figure 5.1: Multimodal feedback for mid-air gestures in a simulated driving scenario. Feedback types are 1) Visual, 2) Auditory, 3) Peripheral Lights, and 4) Cutaneous Push.

additional workload, and secondary task performance. The second key point was to measure the impact of gesturing in mid-air on driving. Finally, this study aimed at investigating the impact of feedback combinations on user preference.

The three main aims of this experiment are to: (1) determine the impact of mid-air gesture feedback on driving safety; (2) measure the impact of mid-air gestures on driving safety; and (3) analyse which feedback combinations were most preferred by the participants. These aims begin to contribute an answer to the third research question of this thesis:

> **RQ3:** How do *multimodal* mid-air gesture feedback techniques influence driving performance and in-car interaction (*Experiments 5, 6, & 7*)?

5.2.2 Methodology

The study design is the same as in Study 4 (Section 4.3) unless it is explicitly stated that there is a difference (i.e. sections Feedback Design, Measures, Hypothesis, Procedure, and Participants).

Feedback Design

This section describes only the changes made in the design of the feedback from Study 4 (Section 4.3). Two key points have been added to each technique: 1) *Attention* feedback was presented after a 500 ms dwell (to avoid accidental gesture input) of the hand in the gesture sensing area; and 2) display of *system state* after each successful gesture execution.

System Attention Feedback It is important that a mid-air gesture system informs the driver that it "sees" them and is ready for interaction [104]. This lessens driver's cognitive load and increases usability of the system [50]. In this study, the system's readiness to interact was conveyed in the following fashion: in Visual feedback, the screen "woke up" from a dimmed interface to a brightly lit one; during the AF condition, a short c5 note of 150 ms duration was played; in CPF, L3 pushed for 150 ms against the drivers palm; and in the PLF condition, a white dim light pulsed for 350 ms (it was impossible to pulse it quicker). The feedback was presented after a 500 ms delay upon entrance of the hand in the gesture interaction area. The introduction of a 500 ms dwell was based on [98] to avoid unintentional gesture input.

Visual Feedback (VF) was unchanged from Study 4 with one addition: *Attention* feedback (see above).

Auditory Feedback (AF) displayed system state through non-speech feedback followed by speech. Total duration of feedback was then 500 ms. Speech feedback (200 ms) displayed the system state by saying the current value of the system state (a number from 0 to 10). The non-speech Earcons are unchanged from Study 4 (300 ms). The non-speech tones were generated in Audacity [231] (Table 4.1). The speech feedback was spoken by a male US American voice (www.cereproc.com/ Voice: Nathan. Accessed 2016-01-31).

Gesture	Non-speech	Duration	Speech
V on	g#4 $\rightarrow$ c5	300 ms	on
V off	c5 $\rightarrow$ g#4	300 ms	off
SL	c4 $\rightarrow$ c4	250 ms	$\uparrow \{0 - 10\}$
SR	c5 $\rightarrow$ c5	250 ms	$\downarrow \{0 - 10\}$
CW	c4 $\rightarrow$ b4	250 ms	$\uparrow \{0 - 10\}$
ACW	b4 $\rightarrow$ c4	250 ms	$\downarrow \{0 - 10\}$
Entrance	c5	150 ms	-

Table 5.1: This table shows the Auditory feedback used for each gesture. The arrow in Non-Speech describes the transition from one note to the next. Duration describes the length of each non-speech unit. Speech stands for spoken gesture feedback; e.g. feedback for SL would be an increment of a number between $\{0 - 10\}$, and a decrement for SR. In total the feedback lasted 500ms.

Cutaneous Push Feedback (CPF) was extended by one addition. When the hand entered the interaction box, L3 was presented for 150 ms. L3 was chosen since it had a high recognition rate of 90.20% in Study 2 (Section 3.3). The aim of the feedback patterns was to provide distinct notifications for each gesture. It was impossible to design system state feedback via Cutaneous Push, which did not elongate the interaction. Cutaneous Push functioned as secondary feedback to confirm the primary, and more rich feedback type such as Visual, Auditory, and Peripheral Lights.

Gesture	Pins	Duration	Time b/w Pins
V	all	150 ms	-
SL	L1 → L2	2 x 150 ms	50 ms
SR	L2 → L1	2 x 150 ms	50 ms
CW	L3 → L2 → L1	3 x 166 ms	-
ACW	L1 → L2 → L3	3 x 166 ms	-
Entrance	L3	150 ms	-

Table 5.2: This table shows the Cutaneous Push feedback used for each gesture. The arrow in Pins describes the transition from one feedback location on the palm to the next. Duration describes the length of each pin presentation.

Peripheral Light Feedback (PLF) was changed to display system state. For successful (anti-)clockwise motion displayed blue lights either incrementing to the right or decrementing to the left (Figure 5.1). The LED strip was divided into 10 chunks (107 LEDs on the strip, 10 LED lights per chunck), representing system state. With each successfully executed gesture, another chunck of LED strip would be added to the blue light pulsing. The lights pulsed for 500 ms.

Feedback for the swiping motions left and right was a yellow light animation mimicking the direction of the gesturing hand. Repeated swipe right motions would increase the length of the animation, and swipe left would decrease the length of the animations. The solution to providing system state for swiping movements was to — similar to the circle motion — increase the number of illuminated LED lights. This resulted in increasingly longer/shorter animations towards the swiped direction. Duration of the animation was 500 ms. The colours blue (circle) and yellow (swipe) were chosen because these can be effectively discriminated in the periphery [240] and have been shown to be an effective display in high data driven environments like aeroplane cockpits [168]. Victory gesture feedback was unchanged from Study 4.

On entrance of the hand in the interaction box, the strip would pulse for 350 ms in a dim white light. This longer display of the system attention feedback was a result of the limitations of the LED strip used. A shorter pulse of 150 ms was barely perceivable and therefore had to be elongated to 350 ms, via trial and error.

Feedback modalities were combined as follows: Auditory-Visual (AV), Auditory-Cutaneous Push (ACP), Auditory-Peripheral (AP), Cutaneous Push-Peripheral (CPP), and Cutaneous Push-Visual (CPV). Auditory-Visual feedback functions as baseline for this study since it has already been used in the literature and commercially available cars for mid-air gesture interaction [98, 108]. Visual-Peripheral was not tested because both techniques use the same sensory channel for information throughput; to avoid overloading a single channel it was decided not to use this combination.

Apparatus

The laboratory setup for Study 5 differed in one final point from Study 4's layout: the webcam was place on top of the steering wheel base looking up to the driver; in Study 4, it was placed on top of the 27 inch screen. An SVM classifier with a linear kernel was trained on 5127 images obtained during a pilot study. Input data for the classifier were 3D vectors for each eye and head pose rotation. The SVM model classified 91.54% eyes-off-the-road time correctly (10-fold cross validation).

Measures

The Independent Variable was mid-air gesture feedback technique. There were five levels: Auditory-Visual (AV), Auditory-Peripheral (AP) , Auditory-Cutaneous Push (ACP), Cutaneous Push-Visual (CPV), and Cutaneous Push-Peripheral (CPP). The Dependent Variables were the same as in Study 4.

Hypotheses

- **H1** Visual distraction from the primary driving task is significantly decreased in the AP, ACP, CPA conditions compared to AV and CPV;
- **H2** Lane deviation will not significantly differ between the feedback conditions;
- **H3** Non-visual conditions will result in a significant decrease of perceived workload;
- **H4** Participants will prefer combinations with Visual feedback the least.

Research has shown, that even if no visual attention is required (such as with voice entry) users tend to look towards the loudspeaker or microphone, awaiting system response [32, 33, 77]. Therefore, hypothesis **H1** predicts increased EORT from modality combinations including Visual feedback, even though there will be a non-visual option to fall back on. Consequently, hypothesis **H3** predicts higher workload for conditions with Visual feedback, resulting in hypothesis **H4** which expects participants to dislike combinations with Visual feedback the most.

Since results from the unimodal feedback study (Chapter 4) showed no impact of modality on driving behaviour, hypothesis **H2** does not predict any differences in driving performance across the feedback types.

Procedure

There were two differences between the driving task in Study 5 compared to Study 4. Firstly, participants started at the outmost left lane of a five lane motorway and had to steer the car into the middle lane. The low lane deviations from previous studies led to the assumption that an "optimal" steering angle was found and maintained throughout the study. This aim of this change is to assess whether that was true.

Secondly, each modality block was tested twice resulting in 10 blocks in total. The entire experiment lasted 90 minutes.

Participants

Eighteen participants (10 females) ranging from 20 to 35 years of age (μ 26.72 σ 4.29) were recruited via the University of Glasgow's student online forum. Of these 18, eight participants obtained their driving license in a country with Left-Hand-Traffic (LHT) and 10 a Right-Hand-Traffic (RHT) license. A total of eight participants indicated that they had no prior experience with mid-air gesture interfaces but none had participated in the previous study. All participants were right handed. They were paid £10 at the end of the study.

5.2.3 Results

Gaze Behaviour

Average glance duration was 798 milliseconds per gesture. A Shapiro Wilks test showed that gaze behaviour data was non-normal ($W = 0.387, p < 0.001$). A repeated measures ANOVA on Aligned Rank Transformed (ART) data tested whether there were mixed effects of feedback combination and gesture on gaze behaviour. There was a significant impact of condition on EORT ($\chi^2(4) = 19.978, p < 0.001$) and gesture on EORT ($\chi^2(12) = 4.474, p < 0.001$), however no mixed effects ($\chi^2(48) = 0.7625, p = 0.881$). A pairwise Tukey post-hoc test revealed significant differences on impact of feedback on EORT between: Cutaneous Push-Visual and all other conditions, CPV-CPP ($p < 0.001$), CPV-AP ($p < 0.001$), CPV-ACP ($p < 0.001$), and CPV-AV ($p = 0.003$); AV and AP ($p = 0.016$), AV and CPP ($p < 0.001$);

and ACP and CPP ($p = 0.011$) (Figure 5.2). A pairwise post-hoc Tukey revealed that if compared to Victory, every other gesture but ACW2 ($p = 0.924$) had a significant impact on looking away time (Figure 5.3).

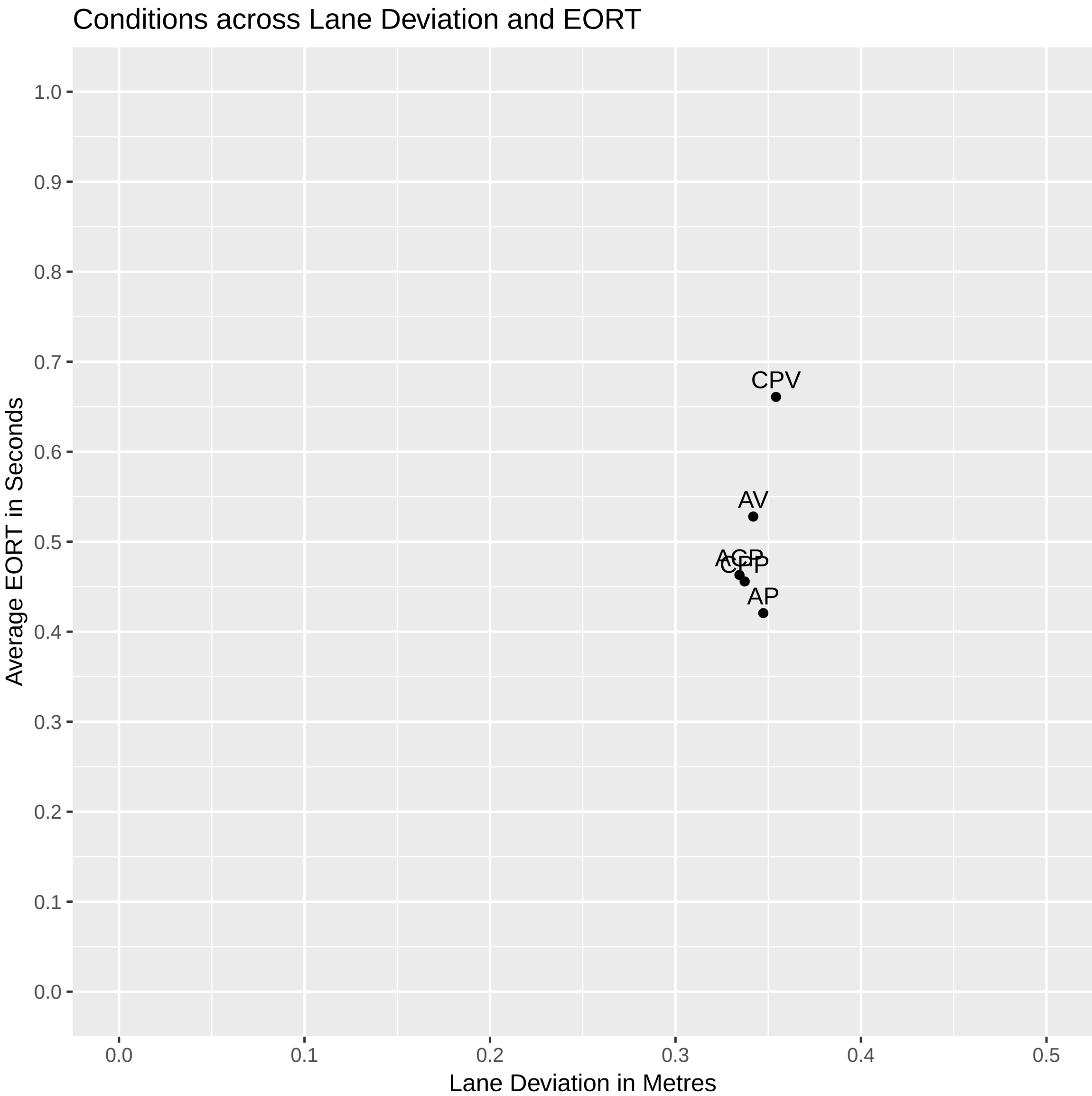
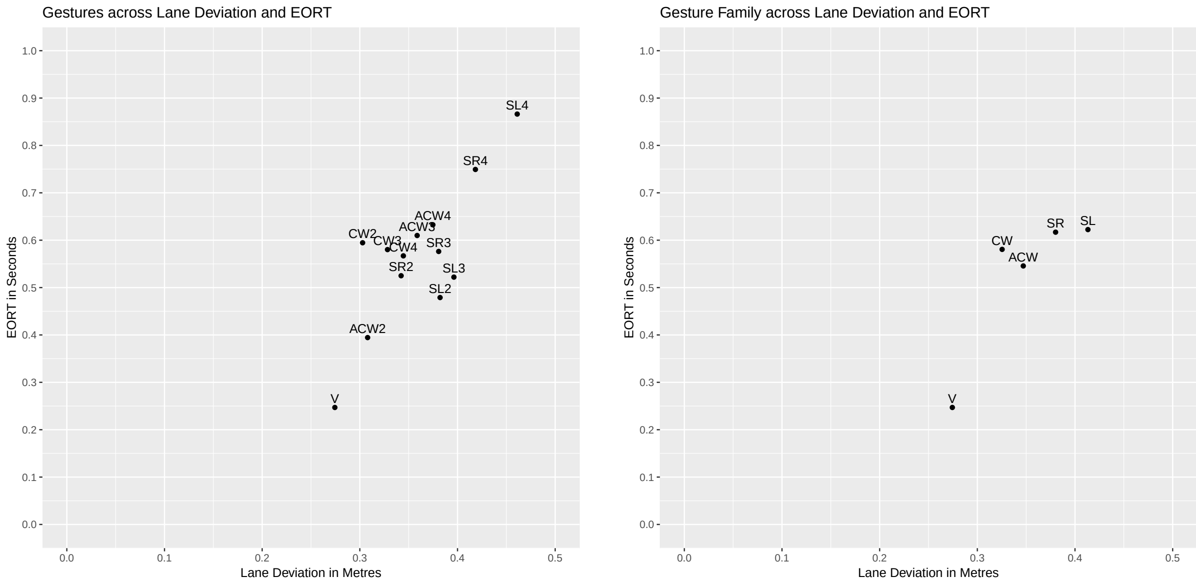


Figure 5.2: Average driving and glancing behaviour dependent on feedback conditions. The modalities were: Auditory-Cutaneous-Push (ACP), Cutaneous Push-Peripheral (CPP), Auditory-Visual (AV), Auditory-Peripheral (AP), and Cutaneous Push-Visual (CPV).

Driving Performance

A Shapiro Wilks test showed that the driving data is non-normal ($W = 0.870, p < 0.001$). ANOVA of ART data showed gestures had a significant impact on lane deviation ($\chi^2(12) = 8.952, p < 0.001$), but not feedback type on lane deviation ($\chi^2(4) = 2.315, p = 0.055$). Pairwise post-hoc Tukey tests revealed that the following gestures had impact on lane devia-



(a) (b)

Figure 5.3: Impact of gestures (left) and gesture families (right) on lane deviation and eyes-off-the-road time. Gestures: ACW: Anti-clockwise, CW: Clockwise, SL: Swipe Left, SR: Swipe Right, V: Victory.

tion: compared to Victory, CW4 ($p < 0.047$), ACW3 ($p < 0.001$), ACW4 ($p < 0.001$), SL2 ($p < 0.001$), SR3 ($p < 0.001$), SL3 ($p < 0.001$), SR4 ($p < 0.001$), and SL4 ($p < 0.001$) had significantly higher impact (Figure 5.2).

ANOVA using ART data showed that gesture family influences lane deviation (Figure 5.3) significantly ($\chi^2(4) = 24.135, p < 0.001$), with Victory resulting in least impact compared to CW ($p < 0.001$), ACW ($p < 0.001$), SL ($p < 0.001$), and SR ($p < 0.001$). Clockwise family had less impact on lane deviation compared to SL ($p < 0.001$), and SR ($p = 0.018$); anticlockwise had less impact than SL ($p = 0.005$).

Gesturing Performance

Average gesturing performance was at 75.35%. A binomial regression was run on whether condition influences gesturing success ($z = 6.842, p < 0.001$), showing that Cutaneous Push-Visual ($z = -4.837, p < 0.001$) and Cutaneous Push-Peripheral ($z = -3.210, p < 0.001$) significantly influenced gesture performance negatively. Average gesture success depending on condition was: 84.37% for AV, 81.80% for ACP, 80.51% for AP, 73.38% for CPV, and 77.34% for CPP. Binomial regression showed, that gesture family influenced success ($z = 3.395, p < 0.001$); circle clockwise (CW) average performance was at 72.35%, ACW at 86.07%, SL at 72.74%, SR at 62.86%, and V at 97.48%. Finally, binomial regression showed, that individual gestures influenced success ($z = 3.837, p < 0.001$). Individual gesture performances were for CW2 at 77.05%, CW3 at 71.17%, CW4 at 68.82%, ACW2 at 87.64%, ACW3 at 88.82%, ACW4 at 81.76%, SL2 at 79.41%, SL3 at 69.41%, SL4 at 69.41%, SR2 at 70.58%, SR3 at 66.86%, SR4 at 51.17%, and V at 97.48%.

Further binomial regression analyses revealed that RHT trained participants had significantly better gesturing results than LHT participants ($z = 4.43, p < 0.001$), with 80.22% gesturing success for LHT participants, and 78.67% for RHT participants. Spearman rank correlation showed no impact of gender on gesturing success ($S = 953.41, p = 0.518, \rho = -0.168$).

Hands off the wheel duration was non-normal ($W = 0.81422, p < 0.001$). A repeated two-way ANOVA on aligned rank transformed HoW data showed, that condition significantly influences HoW duration ($\chi^2(4) = 3.242, p = 0.012$), as well as gesture family ($\chi^2(4) = 113.460, p < 0.001$), however there is no mixed effect of both on HoW ($\chi^2(16) = 0.489, p = 0.951$). Post-hoc multiple comparison showed a significant difference between Audio-Peripheral and Cutaneous Push-Visual ($p = 0.004$), with TV impacting HoW duration the least. Post-hoc multiple comparison showed that Victory gesture impacts HoW duration the least ($p < 0.001$). Spearman's rank test was run to determine whether there is a correlation between HoW time and successful gesture execution. No significance was found ($S = 3240, \rho = -0.107, p = 0.601$).

Qualitative Data

A MANOVA ($\chi^2(4) = 0.6146, p = 0.902$) analysis showed that there is no significant effect of feedback type on workload; neither mental, physical, or temporal demand, nor on performance, effort or frustration (Figure 5.5).

Each participant ranked the feedback types from most to least preferred (Figure 5.5). Analysis of the questionnaire showed that participants preferred Auditory-Peripheral feedback most, followed by AT and TA. Both Visual feedback combinations were preferred least, particularly the CPV condition.

5.2.4 Discussion

In this section, the effects of five bimodal types of feedback on mid-air gesture interaction during simulated driving were investigated. The results provide insights into the effects of feedback types on the primary driving task and the secondary gesturing task.

> **H1** Visual distraction from the primary driving task is significantly decreased in the AP, ACP, CPA conditions compared to AV and CPV

The results suggest that providing non-visual feedback for mid-air gesture input is promising since it reduces eyes-off-the-road time significantly (Figure 5.2), with both Visual conditions

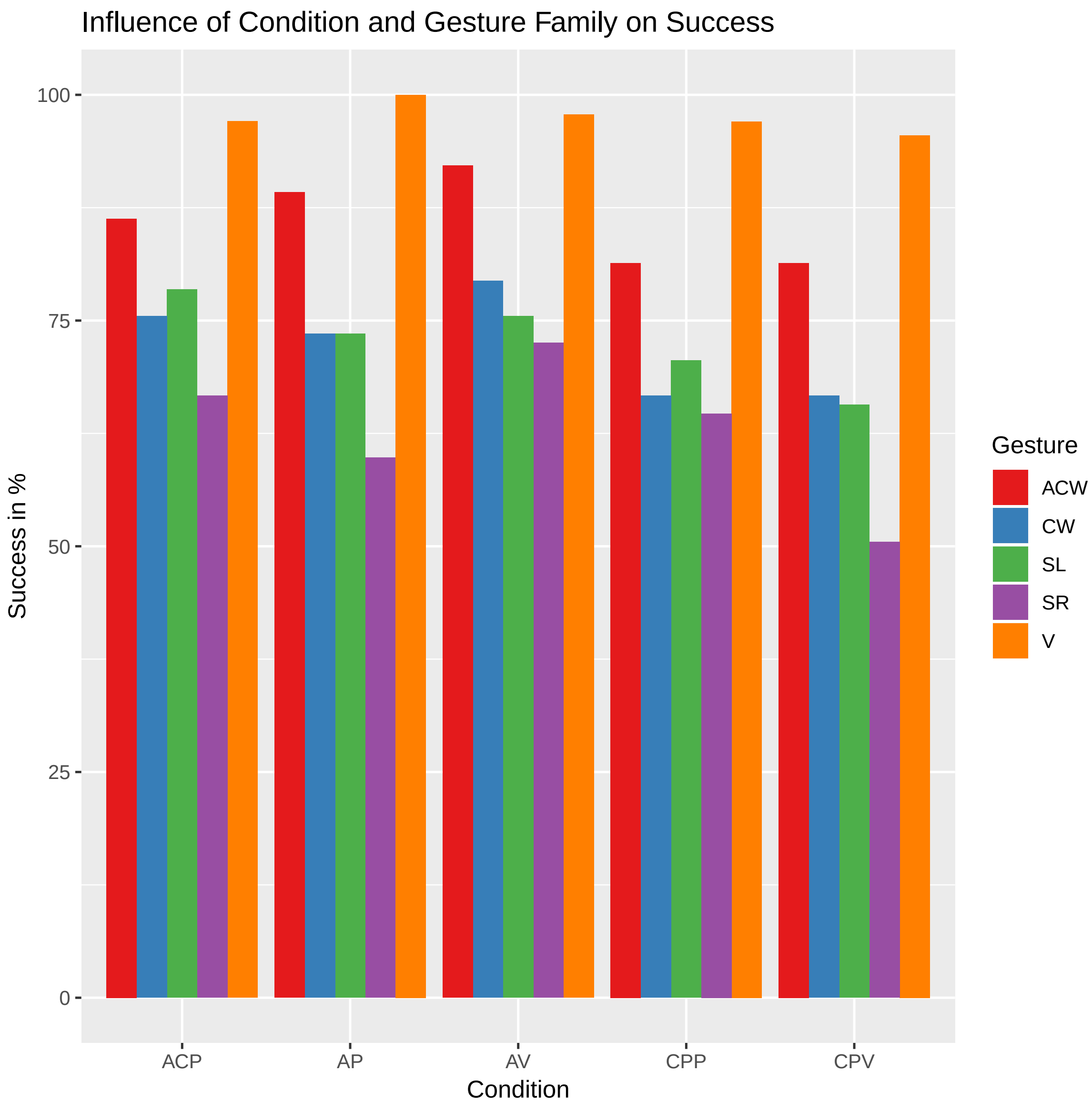
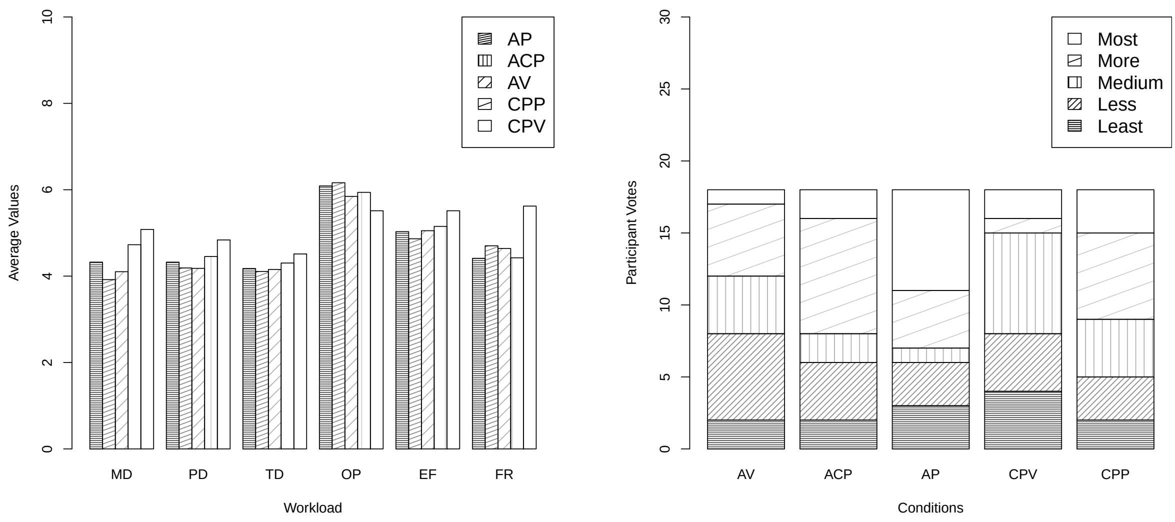


Figure 5.4: Gesture performance accuracy across conditions and gesture families. Conditions from left: Auditory-Peripheral (AP), Auditory-Cutaneous Push (ACP), Auditory-Visual (AV), Cutaneous Push-Peripheral (CPP), and Cutaneous Push-Visual (CPV). Gesture families from top: Circle Anti-Clockwise (ACW), Circle Clockwise (CW), Swipe Left (SL), Swipe Right (SR), and Victory (V).



(a) (b)

Figure 5.5: Left: Results of the NASA TLX questionnaire (MD: Mental Demand, PD: Physical Demand, TD: Temporal Demand, PE: Performance, EF: Effort, FR: Frustration.). Right: User preferences of bimodal feedback. (AV: Audio-Visual, AT: Audio-Cutaneous Push, AP: Audio-Peripheral, TV: Cutaneous Push-Visual, TP: Cutaneous Push-Peripheral).

(Auditory-Visual and Cutaneous Push-Visual) resulting in the most time looking away from the road. Therefore, hypothesis **H1** was accepted.

> **H2** Lane deviation will not significantly differ between the feedback conditions

Hypothesis **H2** was accepted since there was no difference in lane deviation across the conditions (Figure 5.2). The lack of significant impact of feedback type on driving performance might be due to: 1) the secondary task duration was too short (average glance duration was less than 2000 ms). It has been shown that if drivers glance off the road for less than 2 seconds it has no impact on lane deviation [241, 31]; 2) default level of noise caused by gesturing; 3) over time, participants found the optimal steering wheel position for least lane deviation.

> **H3** Non-visual conditions will result in a significant decrease of perceived workload

Hypothesis **H3** was accepted since no difference in workload was detected between the conditions. The motivation for investigating bimodal feedback was to see if redundantly presenting information across two modalities could reduce the workload associated with interaction. The results show that workload was similar for the four feedback combinations, supporting

	EORT	Lane Dev	Gesture	Workload	User Preference
CP-V	X	✓	X	✓	X
A-V	X	✓	✓	✓	X
A-CP	✓	✓	✓	✓	✓
CP-PL	✓	✓	X	✓	✓
A-PL	✓	✓	✓	✓	✓

Table 5.3: Significant impact ("X") of the feedback types on EORT, driving and gesturing performance, mental workload and user preference. Cutaneous Push and Visual feedback had a significant impact on EORT, gesture performance and resulted in low preference by the users. The results suggest that CP-V feedback for mid-air gestures impacts the driver negatively instead of supporting gesture interaction.

the use of combinations of Audio, Peripheral Visual, and Cutaneous Push feedback. These novel combinations had similar cognitive demand to the baseline Audio-Visual pair, with the advantage of eliminating the need to glance at the console screen.

H4 Participants will prefer combinations with Visual feedback the least

Participants preferred Auditory-Peripheral feedback most. Participants P11 and P19 mentioned that the Peripheral component helped to perform the gestures, in particular the swiping gesture, and the auditory component reduced mental demand. They described the Peripheral Lights animation of the swiping motion as indicating how they were supposed to swipe themselves, i.e. parallel to the table top executing a swift motion. This is in accordance with Freeman *et al.*s [239] observation, that participants appreciate system help to aide them in gesturing correctly. As Visual feedback combinations were preferred the least, hypothesis **H4** was accepted.

Best gesturing performances were achieved during conditions with Auditory feedback, worst performances during the Cutaneous Push-Visual and Cutaneous Push-Peripheral Lights feedback conditions (Figure 5.4). Interestingly, participants perceived their gesturing performance highest during Auditory-Peripheral feedback; however, quantitative analysis shows that Auditory-Visual resulted in the highest performance. Cutaneous Push-Visual feedback caused the highest EORT, highest lane deviation, worst gesturing performance, and was ranked the least preferred feedback modality. The high success rate for AV can be explained with participants being most familiar with Audio-Visual feedback in driving situations.

Feedback on entrance of the hand into the sensing system's field of view was shown to be unnecessary. The car cockpit and the gesture interaction area are limited and muscle memory sufficed for the user to place their hand inside the interaction box.

5.2.5 Limitations

The results here are again, are best case scenarios, because feedback is only provided to expected gestures. Despite the changes to the size of the interaction box, participants still struggled with the swiping and the circling. An important question to consider was: are swipe gestures inherently bad, or was Leap Motion implementation prone to false positives?

Some gestures seem to be inappropriate for car cockpit usage, especially the swipe. It is impractical to "reset" the swipe outside the interaction box in a small area such as above the gear stick, without causing accidental reverse swipes. The swipe gesture is very unsuited to be used in a confined space, but production cars still use them. As there is scope for improving the robustness of its detection, the next study will propose a different swipe recognition technique, instead of omitting it from further analysis completely.

Finally, the camera used to film participants' eye gaze had to be relocated from the top of a monitor to the top of the steering wheel base. The camera filmed participants through the rim of the wheel in an upwards angle. The used angle of the camera might not have been optimal for eye-gaze classification, potentially explaining the increase in EORT compared to Study 4. The location of the camera will be reconsidered in the next iteration.

5.2.6 Summary

This section contributes novel bimodal feedback techniques for mid-air gesture interaction in a driving scenario. The aims of this experiment were to: (1) determine the impact of mid-air gesture feedback on driving performance; (2) measure the impact of mid-air gestures on driving safety; and (3) analyse which feedback combinations were most preferred by the participants. These aims began to contribute an answer to the third research question of this thesis:

> **RQ3:** How do *multimodal* mid-air gesture feedback techniques influence driving performance and in-car interaction (*Experiments 5, 6, & 7*)?

Of the four hypotheses identified in Section 5.2.2, all but **H4** were accepted. The results of this study show that the presented non-visual feedback combinations cause less eyes-off-the-road time, and have no negative effects on driving performance nor mental demand compared to Visual feedback combinations.

5.2.7 Comparison of Study 4 and Study 5

A comparison between the results from Study 4 and 5 show that mid-air gesturing in cars benefits from bimodal feedback, especially the negative impacts of Visual feedback are decreased with bimodal displays. Similar to the findings from Study 4, feedback modalities with a Visual component led to higher EORT and were the least preferred by users (Table 5.3). Visual feedback condition benefited from a bimodal combination (e.g with Cutaneous Push and Auditory) as it decreased the negative impact which visual distraction has on the driver's ability to control the car. Bimodal feedback further decreased the negative impact of Visual on perceived workload, especially on mental and physical demand.

The Cutaneous Push modality also benefited from bimodal feedback. As discussed, CP is a low resolution technique which can function as secondary feedback to confirm the primary, and more rich feedback type such as Visual, Auditory, and Peripheral Lights. The addition of CP benefited Peripheral Lights by decreasing its negative impact on driving performance.

Gesturing performance has overall increased due to bimodal feedback and the addition of system state feedback from Visual with 74.56%, Auditory with 73.14%, Peripheral Lights with 67.36%, and Cutaneous Push with 61.22% in Study 4 to 84.37% for AV, 81.80% for ACP, 80.51% for AP, 73.38% for CPV, and 77.34% for CPP in Study 5.

The feedback modalities did not affect driving performance or increase mental demand, suggesting it can support gesture input without increasing distraction and putting safety at risk. By distributing interaction feedback across multiple modalities, drivers can focus more on the primary task of driving.

5.3 Study 6: Bimodal Mid-air Gesture Feedback during the Lane Change Task

Mid-air gestures in cars are now being used by an increasing number of drivers on the road. Usability concerns mean good feedback is important, but a balance needs to be found between supporting interaction and reducing distraction in an already demanding environment. Visual feedback is most commonly used, but takes visual attention away from driving. This thesis has investigated non-visual alternatives; however, they lack the expressive capabilities of high resolution screens, but are intended to allow drivers to focus on the driving task. Studies 4 (Chapter 4) & 5 (Section 5.2) found that non-visual feedback modalities, especially when combined bimodally, offered just as much support for interaction without negatively affecting driving performance, visual attention and cognitive demand. These results provide compelling support for using non-visual feedback from in-car systems, supporting input whilst letting drivers focus on driving.

However, the results presented so far only apply to driving straight on a motorway. The aim of the previous studies was to obtain a clean measure of the impact of gesturing and feedback modality on car control (lane deviation). The next key question to investigate is whether these results also apply on more challenging driving. This section presents a simulated driving study where users performed mid-air gestures whilst performing a Lane Change Task (LCT). This is a standard task (ISO standard 26022:2010) used in automotive studies to investigate the demands of secondary tasks whilst driving (e.g., responding to navigation instructions or interacting with a system). The LCT will inform us which feedback modalities support safe driving, and whether participants prioritise gesturing or driving.

This study builds on the findings from Study 5 (Section 5.2), evaluating bimodal feedback with combinations of four feedback types: Visual (standard car console screen), Auditory (headphones), Peripheral Visual (LED display behind steering wheel) and Cutaneous Push (solenoids on the steering wheel) (Figure 5.1).

Finally, as discussed previously (Section 5.2.5), there is scope for improving the robustness of swipe gesture detection. It is important to answer the question whether swipe gestures are inherently bad in car cockpits, or whether the Leap Motion's implementation was prone to false positives. This section offers an alternative swipe recognition to Leap motion's built in solution.

5.3.1 Research Aims

The aim of this study was to measure the impact of gesture feedback modalities on more challenging driving. Therefore, participants performed the Lane Change Task along with the mid-air gesturing task. The first aim of this study was to continue providing an answer to the third research question of this thesis:

> **RQ3:** How do *multimodal* mid-air gesture feedback techniques influence driving performance and in-car interaction (*Experiments 5, 6, & 7*)?

The second aim of this study was to investigate whether more challenging driving has an impact on mid-air gesture interaction. And if so, which feedback modality is most suited to support safe driving while engaging in gesture interaction. One key question is whether participants have a preference to execute gestures or the the lane change, when prompted simultaneously. Therefore, this study starts to contribute to the fourth research question of this thesis:

> **RQ4:** What effect does multimodal mid-air gesture feedback have on interaction in more *challenging driving* (*Study 6 & 7*)?

The main aims of this experiment are to: (1) determine the impact of mid-air gesture feedback on driving safety; (2) investigate which mid-air gesture feedback modality supports safe driving during lane change manoeuvres; and (3) analyse which feedback combinations were most preferred by the participants.

5.3.2 Methodology

The study design is the same as in Study 5 (Section 5.2.2) unless it is explicitly stated that there is a difference (i.e. sections Feedback Design, Hypothesis, Procedure, and Participants).

Feedback Design

The design of the feedback modalities was the same as in Study 5, but Cutaneous Push-Visual was omitted as a feedback technique since it resulted in the worst performance and was ranked as least preferred by participants in Study 5 (Section 5.2).

Swipe Gesture Recognition Design

Two changes were made to improve swipe gesture recognition. Firstly, Leap Motion's swipe gesture is recognised via long, linear movement of a finger. The swipe gesture ends when the finger changes directions or moves too slowly [242]. Improvements to swipe recognition were attempted by classifying long, linear movement of the entire hand rather than just a finger.

Secondly, Leap motion's solution allows for multiple swipe gesture detection within a single execution due to Leap motion's default minimum swipe duration which is 150 milliseconds. Duplicate swipe motions can be picked up if the tracker loses the current finger/hand, rediscovers it, and classifies the ongoing motion as a second long, linear movement. The proposed improvement is based on the assumption that a successful swipe motion lasts for minimally 500 milliseconds. Therefore, the number of possible swipe motions was limited to a single one within half a second. A pilot test with one participant showed, that correct swipe gesture execution is achievable more easily, and less frustratingly.

Lane Change Task

The Lane Change Task (LCT) (ISO standard 26022:2010) aims at measuring the decrease in driving performance while conducting a secondary task. Therefore, the result of the LCT serves as an estimate of the demand of the secondary task [243]. From the instruction to change lane until the car reaches the target lane, its position was measured for LCT analysis (Figure 5.6). The average time to complete a single lane change task on a motorway is between 5.8 seconds [244] and 6.28 seconds [245]. A lane-change initiation is defined as the time the wheel crosses the lane line. On average, the driver needs the first 4.1 seconds after the presentation of a lane change instruction to comprehend and initiate the lane change

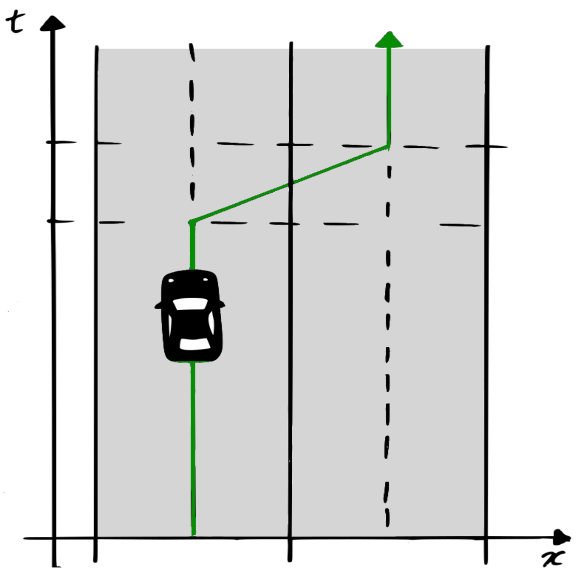


Figure 5.6: Lane Change Task from the left lane to the right lane. The arrow denotes the optimal driving path (i.e. zero lane deviation). Instruction to change is given at 0 seconds; after 4.1 seconds on average [21], the lane change is initiated and completed by 5.8 seconds.

[21]; during this time, lane deviation equals zero in the centre of the *current lane* (left lane on Figure 5.6). During the next˜1.7 seconds, the car transitions towards the target lane (right lane); zero lane deviation is on the *transitioning vector*. These two phases result in the optimal lane change path, where lane deviation is zero (green path on Figure 5.6).

Hypotheses

- **H1** There will be significant difference in gaze behaviour between the Visual and non-visual feedback conditions;
- **H2** There will be no significant difference in lane deviation between the feedback conditions;
- **H3** There will be no significant difference in workload between the feedback conditions;
- **H4** Participants will prioritise Lane Change Task over gesture execution when prompted simultaneously.

Hypotheses **H1** and **H2** are founded on the findings from studies 4 & 5. Both studies found that EORT was significantly increased when a visual component was presented for mid-air gestures, hypothesis **H1** expects similar results. As no impact was found on driving behaviour across the presented modalities in Study 5, hypothesis **H2** expects similar results. Study 5 showed that bimodal displays did not impact workload negatively compared to the other conditions, resulting in the formulation of **H3**. Hypothesis **H4** predicts that as driving is the primary task, drivers will prioritise driving (i.e. LCT) over gesture execution, if both instructions are given simultaneously.

Procedure

Upon arrival, participants were briefed about the study and given an introductory training session. This session was structured like the experiment, but it was shorter. In the training, participants executed each gesture once during each feedback condition. Participants started on the outmost left lane on a five lane motorway and had to steer towards the middle lane. After 30 seconds a trigger was fired to instruct the driver to change a single lane (left/right) and execute a gesture simultaneously. The instructions to change lane were indicated with green arrows on bridge panels over the motorway (Figure 5.1). The arrows pointed down onto the target lane. The lane-change and gesture instructions were presented after random intervals; instructions to gesture were prompted $0-4$ seconds after a lane-change instruction; participants had 30 second to complete both instructions before the next instructions were prompted. The participants were asked to complete both tasks as quickly and safely as possible. The direction of changes was balanced.

During the main experiment, each bimodal feedback block was presented twice, resulting in 8 blocks in total (Figure 5.7). Each block lasted 8 minutes (16 gestures x 30 seconds per lane-change/gesture instruction). Each gesture was executed once resulting in 16 gestures. After each block, participants were asked to fill in a NASA TLX workload questionnaire. At the end of the experiment, participants were asked to fill in a demographics questionnaire. The experiment lasted 90 minutes with briefing and questionnaire.

Participants

Nineteen participants (nine females) ranging from 19 to 53 years of age (μ 26.68 σ 9.23) were recruited via the University of Glasgow's student online forum. Of these 19, 12 participants had a Left-Hand-Traffic (LHT) driving license and seven a Right-Hand-Traffic (RHT) license. A total of 14 participants indicated that they had no prior experience with mid-air gesture interfaces; two participants took part in Study 5. All participants were right handed. Participants were paid £10.

5.3.3 Results

Gaze Behaviour

A Shapiro-Wilk normality test showed that the collected gaze data is non-normal, $W = 0.401, p \leqslant 0.001$. An ANOVA on Aligned Rank Transformed (ART) data was conducted to determine the effects of condition ($\chi^2(3) = 30.301, p \leqslant 0.001$) and gesture ($\chi^2(12) = 6.278, p \leqslant 0.001$) on gaze behaviour (Figure 5.8); both have a significant impact on eyes-off-the-road time. Pairwise comparison tests revealed that Auditory-Visual has significantly

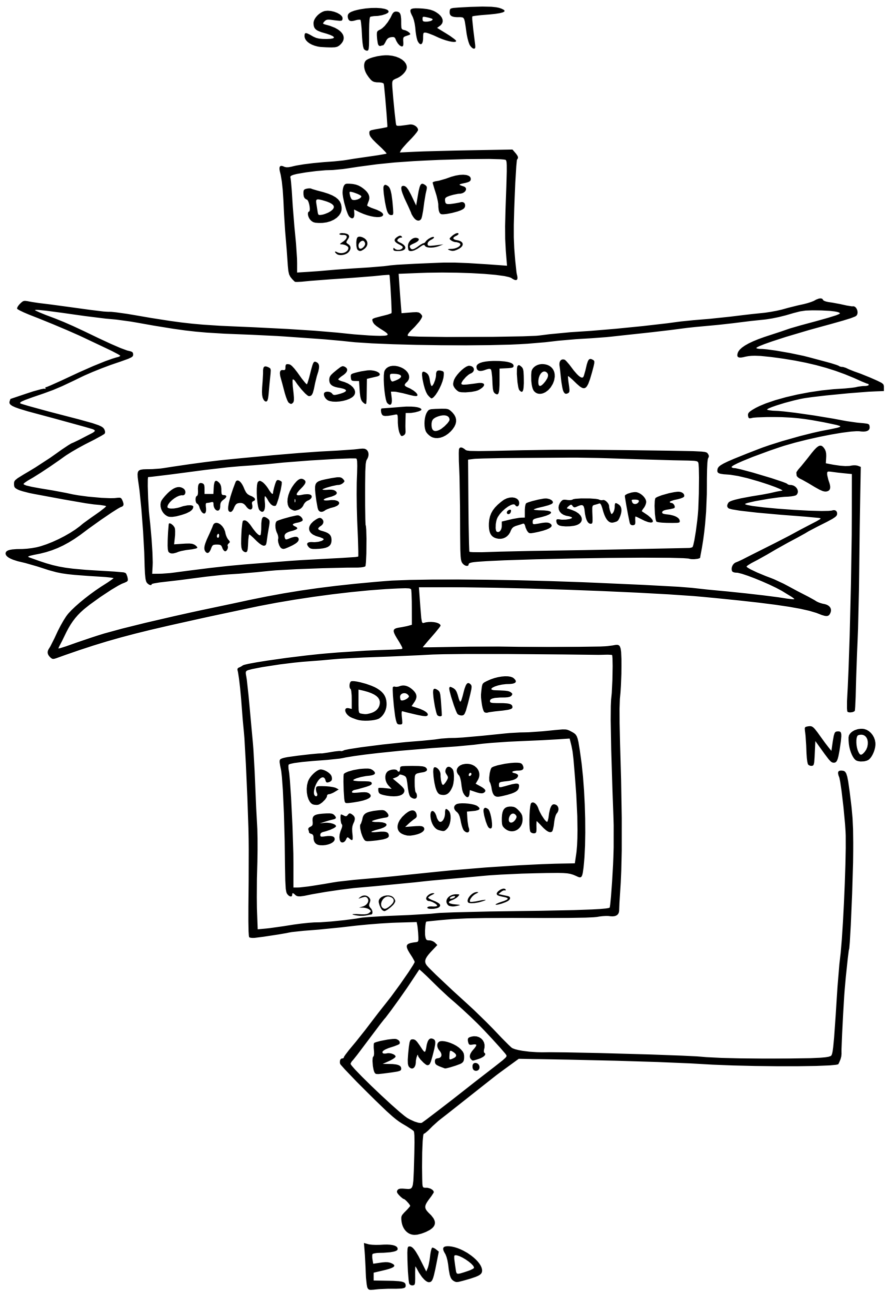


Figure 5.7: Flow chart of a block. A block consists of: participant drives for 30 seconds straight, then a lane change instruction (via bridge panel over the motorway) and a gesture instruction (via pop-up box and auditory instructions for 3 seconds) are given, the participant executes the requested gesture as fast and as accurately as possible, and continues driving for 30 seconds. If it was the last trial of the block, the simulation stops.

increased eyes-off-the-road time compared to the other conditions ($p \leqslant 0.001$). Furthermore, Auditory-Peripheral and Cutaneous Push-Peripheral feedback have significantly differing impact on gaze behaviour ($p \leqslant 0.001$). A pairwise comparison test revealed that gestures the V, ACW2, ACW3, CW2 (EORT $<=$ 0.075 seconds) had a significantly lower EORT than SR2, SR3, SR4, and SL4 (EORT $>=$ 0.125 seconds).

A Friedman's test revealed a significant difference between the types of gestures on gaze behaviour, $\chi^2(4) = 15.898, p = 0.003$. *Post hoc* analysis with Wilcoxon signed-rank test was conducted with a Bonferroni correction applied, resulting in a significance level set at $p < 0.001$. Multiple comparison tests of gesture family means revealed the following significant differences: CC - SR $p = 0.005$; ACW - SR $p = 0.035$; SL - V $p = 0.041$; and SR - V $p \leqslant 0.001$. There were no significant differences between the other types of gestures.

A Spearman's correlation was run to assess the relationship between eye gaze behaviour and gesture performance. There is no statistically significant correlation ($r_s = -0.304, p = 0.062$. An ANOVA on the regression model found no significant main effect of gaze behaviour on driving performance during gesture execution: $chi^2(1) = 0.966, p = 0.324$.

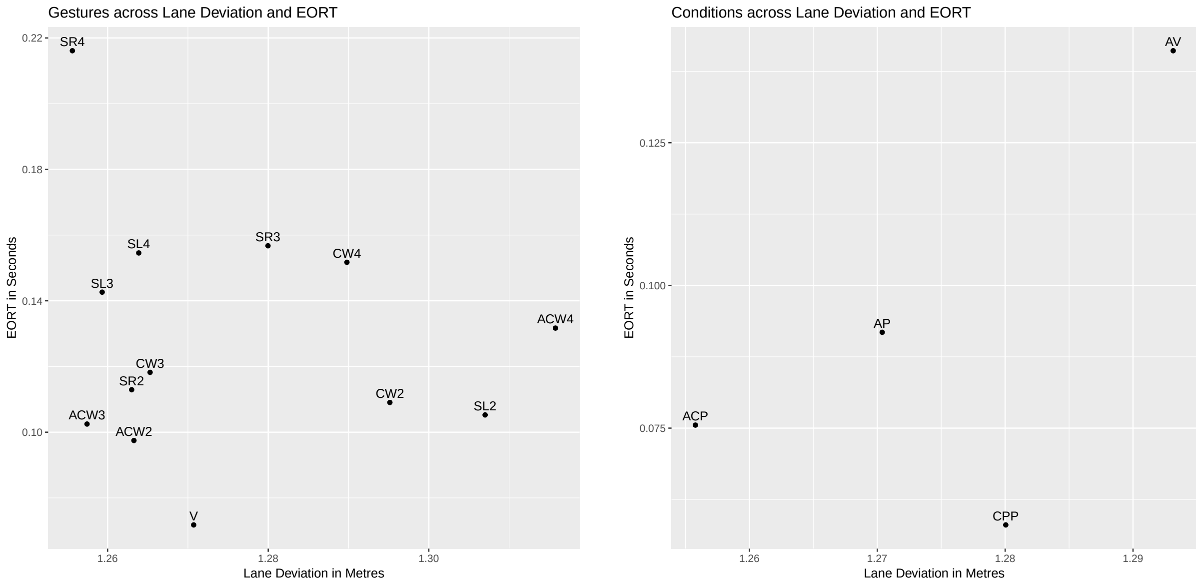
Driving Performance

Root Square Mean Error was used to measure how close the user's driving path was to the ideal driving path [221]. The resulting non-normal distribution was realigned using the ART. A repeated-measures ANOVA showed a significant difference of condition on lane deviation $\chi^2(3) = 4.545, p = 0.003$, however no impact of gesture on lane deviation $\chi^2(12) = 1.131, p = 0.330$ (Figure 5.8). A pairwise comparison test revealed that Auditory-Visual significantly increased lane deviation compared to Auditory-Cutaneous Push, $p = 0.001$. There were no significant differences between any other pairwise comparison.

If instruction to gesture and to change lane were given at the same time, a gesture was labelled as "prioritised" if it was initiated before the lane change task was initiated. A total of 18.06% gestures were prioritised over lane change. Binomial logistic regression was performed to ascertain the effects of gesture prioritisation over lane change task. None of the gestures (CW3 $p = 0.703$, CW4 $p = 0.76$, ACW2 $p = 0.949$, ACW3 $p = 0.239$, ACW4 $p = 0.49$, SL2 $p = 0.346$, SL3 $p = 0.528$, SL4 $p = 0.282$, SR2 $p = 0.245$, SR3 $p = 0.792$, SR4 $p = 0.885$, V $p = 0.849$) had a significant impact on the decision to prioritise it over lane change manoeuvre.

Gesturing Performance

Overall gesture performance across all conditions and participants was 73.45%. A binomial regression was run on whether condition influences gesturing success ($z = 5.237, p <$



(a) (b)

Figure 5.8: Left: Average Eyes-Off-the-Road Time (EORT) and lane deviation across conditions Auditory-Visual (AV), Auditory-Cutaneous Push (ACP), Auditory-Peripheral (AP), and Cutaneous Push-Peripheral (CPP). Right: Eyes-Off-the-Road Time (EORT) and lane deviation across gestures. The gestures: Circle Anti Clockwise (ACW), Circle Clockwise (CW), Swipe Left (SL), Swipe Right (SR), and Victory (V). The numerical value on the abbreviations indicates the number of times the instructed gesture was executed.

0.001), showing that Cutaneous Push-Peripheral significantly decreased successful gesture execution. Average gesture success depending on condition was: 74.37% for AV, 74.23% for ACP, 74.49% for AP, and 70.74% for CPP. Binomial regression showed, that gesture family influenced success ($z = 2.949, p = 0.003$); circle clockwise average performance was at 69.01%, ACW at 76.53%, SL at 59.21%, SR at 44.27%, and V at 96.26%. Finally, binomial regression showed, that individual gestures influenced success ($z = 3.296, p = 0.001$). Individual gesture performances were for CW2 at 73.82%, CW3 at 67.33%, CW4 at 66.21%, ACW2 at 87.41%, ACW3 at 89.40%, ACW4 at 84.56%, SL2 at 68.00%, SL3 at 65.10%, SL4 at 52.66%, SR2 at 58.27%, SR3 at 44.29%, SR4 at 35.81%, and V at 95.47%.

Qualitative Data

MANOVA analysis shows that there is no impact of the bimodal feedback (condition) on any of the perceived workload measures ($\chi^2(3) = 0.472, p = 0.952$). Users preferred Auditory-Visual feedback over the other feedback conditions (Figure 5.10).

Each participant ranked the feedback types from most to least preferred (Figure 5.10). Analysis of the questionnaire showed that participants preferred Auditory-Visual feedback most, followed by ACP. Both Peripheral feedback combinations (AP, CPP) were preferred least.

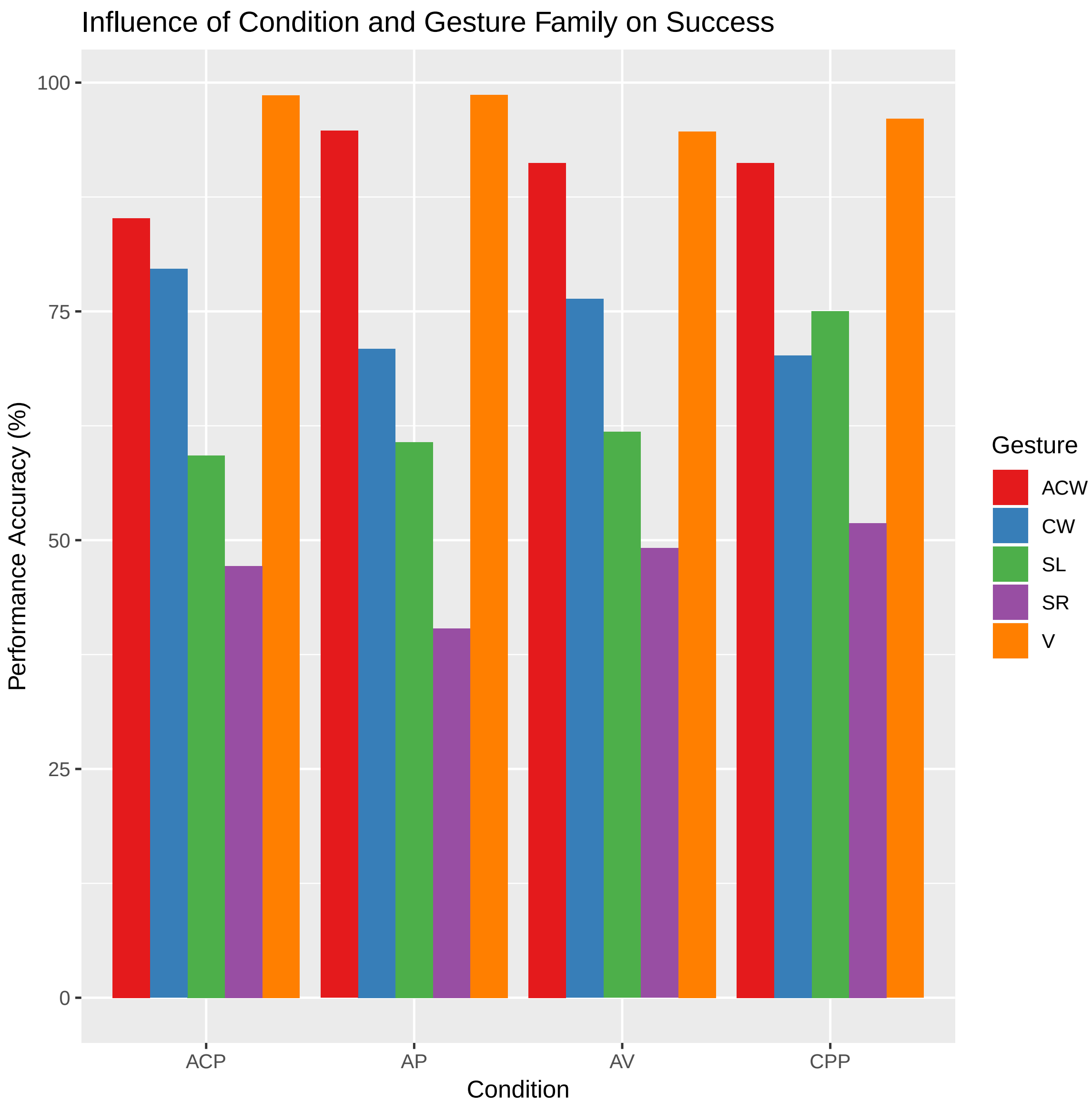


Figure 5.9: Gesture performance success across conditions and gesture families. Conditions from left: Auditory-Peripheral (AP), Auditory-Cutaneous Push (ACP), Auditory-Visual (AV), and Cutaneous Push-Peripheral (CPP). Gesture families from top: Circle Anti-Clockwise (ACW), Circle Clockwise (CW), Swipe Left (SL), Swipe Right (SR), and Victory (V).

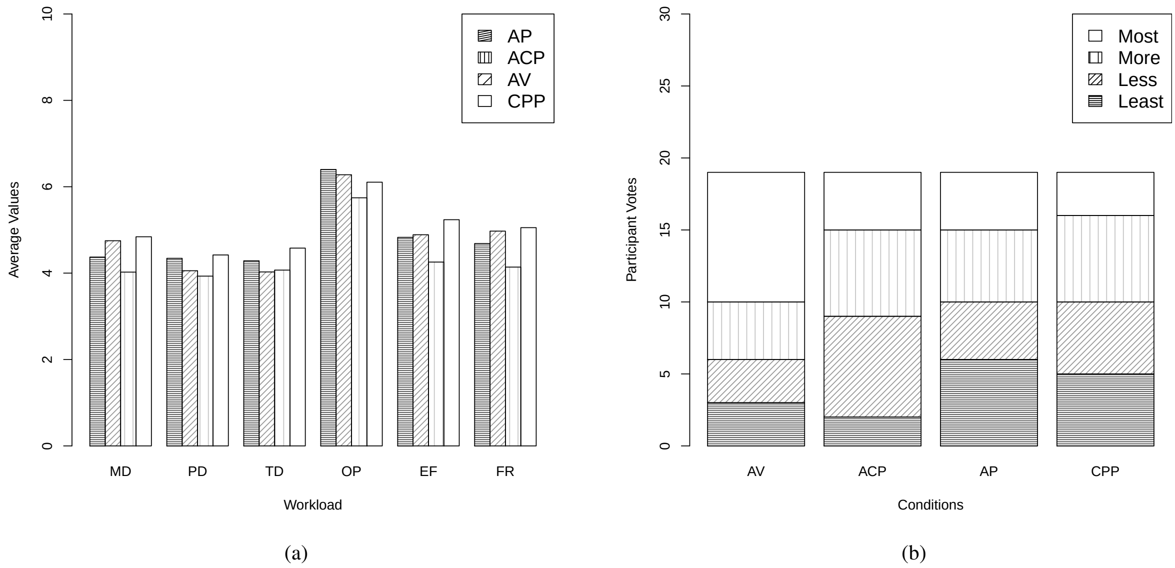


Figure 5.10: Left: Results of the NASA TLX questionnaire (MD: Mental Demand, PD: Physical Demand, TD: Temporal Demand, PE: Performance, EF: Effort, FR: Frustration.). Right: User preferences of bimodal feedback. (AV: Auditory-Visual, ACP: Auditory-Cutaneous Push, AP: Auditory-Peripheral, CPP: Cutaneous Push-Peripheral).

5.3.4 Discussion

This study investigated the efficacy of bimodal feedback for gesture input during a simulated driving task, comparing three novel modality combinations to typical Auditory-Visual feedback. For in-car gesture feedback to be successful, it needs to support interaction whilst importantly not having a negative impact on the driver's awareness of the road and control of the vehicle.

> **H1** There will be significant difference in gaze behaviour between the Visual and non-visual feedback conditions

Auditory-Visual feedback caused significantly longer EORT and more lane deviation, suggesting it is less suitable for mid-air gesture interaction than non-visual techniques, especially during more challenging driving.

> **H2** There will be no significant difference in lane deviation between the feedback conditions

The non-visual information feedback modalities have less impact on the primary driving task, whilst supporting the driver sufficiently for input without glancing at the input sensor or the car console screen (Table 5.4). Therefore, hypotheses **H1** and **H2** were accepted.

	EORT	Lane Dev	Gesture	Workload	User Preference
A-V	X	X	✓	✓	✓
A-CP	✓	✓	✓	✓	✓
CP-PL	✓	✓	X	✓	X
A-PL	✓	✓	✓	✓	X

Table 5.4: Significant impact ("X") of the feedback types on EORT, driving and gesturing performance, mental workload and user preference. Auditory-Visual feedback impacted EORT and driving performance, where bimodal combinations with Peripheral Lights had low user preferences. The results suggest that the Visual component during the A-V condition impacts important aspects of driver safety negatively.

> **H3** There will be no significant difference in workload between the feedback conditions

The results show that mental workload was similar for the four feedback combinations, supporting the use of combinations of Auditory, Peripheral Visual, and Cutaneous Push feedback. These novel combinations had similar cognitive demand to the baseline Auditory-Visual pair, with the advantage of eliminating the need to glance at the console screen. Therefore, hypothesis **H3** was accepted.

> **H4** Participants will prioritise Lane Change Task over gesture execution when prompted simultaneously

If drivers were prompted to gesture and execute a lane change task at the same time, 18.06% of gestures were initiated (i.e. the gesturing hand was taken off the steering wheel) before the driver initiated the driving manoeuvre; analysis showed, there was no significant difference in prioritisation of any gesture over the lane change task. Hypothesis **H4** was accepted.

There was a significant impact of feedback modality on gesturing performance with Cutaneous Push-Peripheral Lights impacting it negatively. Both modalities are low resolution and did not support perception of each other.

Further analysis revealed a significant difference in secondary task performance across gestures. The V gesture yielded highest performance with 95.47% accuracy. The Victory gesture consists of a single static and discrete pose, unlike Circle or Swipe. The worst performing gesture type was Swipe with an overall performance of 44.66% (SR4 with 35.81%), despite the attempt to improve the reliability of the gesture recognition. An explanation is that the number of false negatives increased (two swipes were registered instead of one) increasing frustration and decreasing likelihood of the user to correct the misclassification.

Finally, nine out of nineteen users preferred the Auditory-Visual condition over the other feedback combinations. This high rate may be due to the users being more familiar with

Auditory and Visual than Cutaneous Push feedback. This familiarity resulted in less time and effort needed to learn the system messages. However, it would be beneficial for drivers to learn these messages since there is a clear potential for gestures with Cutaneous Push feedback in the automotive context.

5.3.5 Limitations

A limitation of this study remained to be the robustness of swipe gesture recognition. All swipe gesture performances (SL2, SR3, etc) dropped on average by 15%. The next iteration will look at final adjustments to the swipe motion in an attempt to improve its recognition robustness.

The motivation behind the addition of the LCT was to create an environment which was "more challenging" compared to the previous studies (i.e. studies 1-5). The primary aim was to assess the impact of the different feedback types on the primary driving and secondary gesturing task during "more challenging" driving, not necessarily to create a "challinging" driving task.

5.3.6 Summary

The primary contribution of this section is an investigation of bimodal feedback for in-car gestures during the Lane Change Task. The secondary contribution is compelling support for bimodal, non-visual feedback to support gesture input whilst letting drivers focus on driving.

The main aims of this experiment were to: (1) determine the impact of mid-air gesture feedback on driving safety; (2) investigate which mid-air gesture feedback modality supports safe driving during lane change manoeuvres; and (3) analyse which feedback combinations were most preferred by the participants. These aims continued to contribute an answer to the third research question:

> **RQ3:** How do *multimodal* mid-air gesture feedback techniques influence driving performance and in-car interaction (*Experiments 5, 6, & 7*)?

and began to contribute an answer to the fourth research question of this thesis:

> **RQ4:** What effect does multimodal mid-air gesture feedback have on interaction in more *challenging driving* (*Study 6 & 7*)?

Of the four hypotheses identified in Section 5.3.2, all were accepted. The results of this study show that redundantly presenting feedback about interaction across multiple modalities can reduce the demands placed on drivers, allowing them to make use of the most appropriate information, especially during more challenging driving.

5.3.7 Comparison of Study 5 to Study 6

The main differences between Studies 5 & 6 are the exclusion of Cutaneous Push-Visual feedback and the inclusion of the Lane Change Task. The results show, when comparing user preferences from studies 5 & 6, preferences shifted from Auditory-Peripheral and Cutaneous Push-Peripheral to Auditory-Visual. A reason could be that due to the increase in driving task complexity, drivers felt more comfortable with familiar feedback techniques such as Auditory-Visual rather than Auditory-Peripheral or Cutaneous Push-Peripheral.

Lane deviation increased during Auditory-Visual feedback from Study 5 to 6. As expected, EORT was highest during a feedback modality with a Visual component, which resulted in greater driver distraction, and thus less control over the car.

5.4 Study 7: Ultrasound Mid-air Gesture Feedback during the Lane Change Task

The use of ultrasound haptic feedback for mid-air gestures in cars has been proposed to provide a sense of control over the user's intended actions and to add touch to a touchless interaction [39]. Ultrasound haptics is a unique technique which can provide feedback to the unadorned hand in air. As air pressure is presented to the driver's hand, ultrasound haptics is an inherently eyes-free feedback technique, rendering it a viable solution to mid-air gesture interaction in cars. However, the impact of ultrasound feedback to the gesturing hand regarding lane deviation, eyes-off-the-road time and perceived workload had not been measured prior to this work (conducted in April 2018, and published in September 2018 [166]). Additionally, ultrasound haptics for mid-air gestures is of interest to automotive manufacturers such as BMW [80] and Jaguar [123] who showcased their latest car designs incorporating ultrasound feedback. However, they did this prior to this work, with few insights into the impact of ultrasound haptics on driving, gesturing, and user workload. Therefore, this study investigated the effects of uni- and bimodal presentation of ultrasound feedback on the primary driving task and the secondary gesturing task in a simulated driving environment. The bimodal combinations of ultrasound included Visual, Auditory, and Peripheral Lights.

Despite the fact, that swipe gestures have been shown to be unsuited for the limited interaction area of a car cockpit, it remains an integral part of production vehicle gesture input. Therefore, this study continues to examine multimodal feedback for swipes. However, final changes to its detection have been applied, in an attempt to make it more reliable and less frustrating. It is very important to reduce frustration since a link between driver frustration and increased crash risk has been established [127].

Figure 5.11: Study 7 setup. The Ultrasound array is located to the right of the driver, with the Leap Motion device located next to it. LED strip was placed in front of the driver, the camera recording the driver's eyes on top of the steering wheel base, and the centre console to the right of the driver.

Three final changes have been made to the laboratory setup: 1) to increase fidelity of the driving study, a RSeat RS1 [246] driving seat was installed (Figure 5.11); and 2) a BenQ HD overhead projector [247] was installed to allow for an 80 inch high resolution view of the motorway; and 3) the swipe gesture recognition was further improved.

5.4.1 Research Aims

There is growing interest in multimodal feedback for mid-air gestures, especially the usage of ultrasound haptics which provides tactile sensations in mid-air to the unadorned, gesturing hand. Since ultrasound feedback is a novel technique for mid-air gestures in cars, the main aim of this study was to measure its impact on driving safety and usability. This aim is intended to contribute an answer to the third research question of this thesis:

> **RQ3:** How do *multimodal* mid-air gesture feedback techniques influence driving performance and in-car interaction (*Experiments 5, 6, & 7*)?

The second aim of this study was to continue the investigation of more challenging driving. Due to its novelty, ultrasound feedback has the potential to impact driving and gesturing significantly. The Lane Change Task was designed to measure demands of secondary tasks whilst driving. Furthermore, it allows analysis of the most suited feedback modality for safe driving while gesturing. Therefore, this study continues to contribute to the fourth Research Question of this thesis:

> **RQ4:** What effect does multimodal mid-air gesture feedback have on interaction in more *challenging driving* (*Study 6 & 7*)?

The main aims of this study are to: (1) determine the impact of uni- and bimodal ultrasound mid-air gesture feedback on driving safety; (2) investigate which feedback modality supports safe driving during lane change manoeuvres; and (3) analyse which feedback combinations were most preferred by the participants.

5.4.2 Methodology

The study design is the same as in Study 6 (Section 5.3.2) unless it is explicitly stated that there is a difference (i.e. sections Feedback Design, Apparatus, Measures, Hypothesis, Procedure, and Participants).

Feedback Design

Ultrasound Feedback was presented via an Ultrahaptics array (Figure 5.11) to the right hand of the user. Similar to previous studies, feedback was presented for 500 ms to the palm of the gesturing hand. Each executed gesture was confirmed with a specific feedback pattern. The clockwise motion was confirmed with the presentation of a circular clockwise motion, the anti-clockwise gesture was confirmed with an anticlockwise circular motion. Victory gesture feedback was provided by a 500 ms long ultrasound pulse to the tip of the index and middle fingers. The swipe motion was confirmed with a feedback pattern which mimicked the swiping motion of the hand, i.e. if swiped left, the presented feedback was a wall of air moving from right to left across the palm of the driver. Whenever the hand entered the interaction box, a short pulse was presented to the middle of the palm. The aim of the feedback patterns was to provide distinct notifications for each gesture. As shown by Rutten *et al.* [162] hand scans are one of the best perceivable ultrasound generated shapes, as well as circles [165].

Swipe Gesture Recognition Design

Final changes were applied to the swipe gesture recognition. Solely hand motion along the x-axis were taken into consideration when classifying directional movement. Unintended movements such as up and down (y-axis) or back and forth (z-axis) are of no interest, when detecting swiping from left to right, and vice-versa. These changes were tested in a pilot study.

Apparatus

The laboratory setup for Study 7 differed in three ways from Study 6's layout: 1) a BenQ HD front projector was used to display an 80 inch driving simulator onto a bare wall, 2) a gaming seat to simulate a car cockpit (RSeat RS1), and 3) a TOUCH development kit [248] ultrasound array was placed where the gear stick is located with the Leap motion device at its top (Figure 5.11). The gesture feedback area was determined by the area in which ultrasound feedback can be perceived optimally (i.e. 10-15 cm above device, $14x14$ cm) which is smaller than the Leap interaction area (width: 23 cm; depth: 14 cm; height: 23 cm). However, this should not impact gesturing as the gestures were picked up in the Leap Motion's field of view.

Measures

The Independent Variable was feedback condition. There were five levels: Ultrasound (U), Ultrasound-Visual (UV), Ultrasound-Auditory (UA), and Ultrasound-Peripheral-vision (UP). Visual (V) feedback was chosen as baseline for the study since it has already been used in the literature and in industry for mid-air gesture interaction [98, 108, 31].

Hypotheses

- **H1** Bimodal ultrasound feedback will improve lane keeping ability compared to unimodal feedback;

- **H2** Bimodal ultrasound feedback will improve gesturing ability compared to unimodal feedback;
- **H3** Non-visual feedback modalities will decrease eyes-off-the-road time compared to visual feedback modalities;
- **H4** User workload will be significantly less in the bimodal feedback conditions.

Hypotheses **H1** and **H2** predict improved lane keeping ability and gesturing ability in the bimodal feedback conditions compared to the unimodal ones, since research has shown benefits to gesture interaction [35, 36, 37] and car control [42, 43, 44, 45, 14, 46, 47, 48], if bimodal feedback is presented. Hypothesis **H3** predicts reduced EORT during non-visual feedback, and hypothesis **H4** expects reduced user workload in bimodal conditions, based on previous results (Studies 4-6).

Procedure

The procedure of this study was the same as presented in Study 6 (Section 5.3.2). However, before the study, the participants were introduced to the Utrahaptics demo view [249]. This aided their comprehension of the size of the interaction box for optimal ultrasound feedback perception.

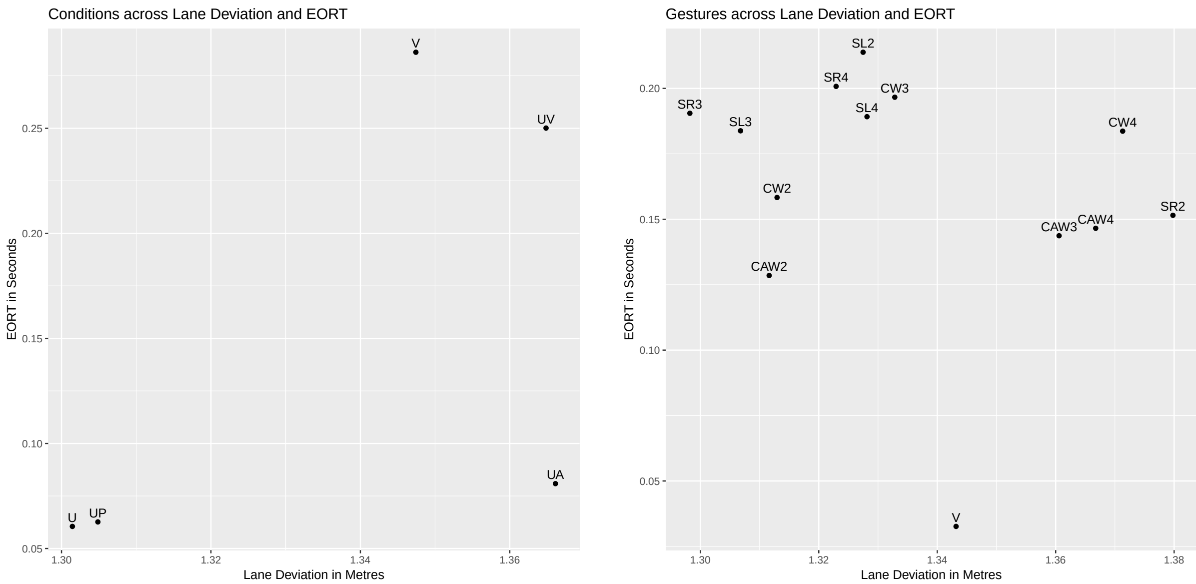
Participants

17 participants (9 females) ranging from 19 to 40 years of age (μ 28.6 σ 6.8) were recruited via the University of Glasgow's student online forum. Seven of the participants had a Left-Hand-Traffic (LHT) driving license and ten a Right-Hand-Traffic (RHT) driving license. One participant was left handed, and one was ambidextrous; both are from the UK. A total of ten participants indicated that they had no prior experience with mid-air gesture interfaces; none participated in previous studies. They were paid £10 at the end of the study.

5.4.3 Results

Gaze Behaviour

Pairwise comparison test revealed that the V gesture had a significantly lower impact on EORT compared to every other gesture. ACW2 had significantly lower impact on EORT compared to SL2 ($p < 0.001$) and SR4 ($p < 0.001$).



(a) (b)

Figure 5.12: Left: Gaze behaviour and driving performance across feedback types (V: visual; U: ultrasound; UV: ultrasound-visual; UA: ultrasound-audio; UP: ultrasound-peripheral). Right: Gaze behaviour and driving performance across gestures (CW: Clockwise, ACW: Anti-clockwise, SL: Swipe Left, SR: Swipe Right, V: Victory). The scales on the axes do not start from 0; the reason behind this choice is to make the output readable (otherwise the dots would be displayed close together and on top of each other).

Driving Performance

Lane deviation was measured from the presentation of the lane change until the next presentation of lane change, as in Study 6. Therefore, lane deviation in the study is high since the transition from current lane into the next lane is taken into account for the analysis.

Collected driving data was non-normal ($W = 0.996, p = 0.004$). ANOVA of ART data showed feedback type influenced lane deviation significantly ($\chi^2(4) = 5.141, p < 0.001$), with Ultrasound and Ultrasound-Peripheral Lights having the least impact on lane deviation (Figure 5.12) compared to Ultrasound-Auditory ($p = 0.032$ for UA, and $p = 0.009$ for UP), and Ultrasound-Visual ($p = 0.031$ for UA, and $p = 0.009$ for UP).

However, no significant impact was found from any gestures ($\chi^2(12) = 1.106, p = 0.351$) nor mixed effects from condition and gestures ($\chi^2(48) = 0.818, p = 0.807$) on car control.

Binomial regression showed there was prioritisation of gesture execution over the Lane Change Task ($\chi^2(12) = 32.321, p = 0.001$), particularly ACW2 ($z = 3.201, p = 0.001$) and SR2 ($z = 3.395, p = 0.001$) were prioritised. However, feedback type had no impact on prioritisation ($\chi^2(4) = 4.057, p = 0.398$).

Gesturing Performance

Overall gesture performance across all conditions and participants was 44.52%. An ANOVA on the binomial regression model found no significant main effect of condition on gesture performance: $chi^2(3) = 3.31, p = 0.346$. Average gesture performance during each condition is V with 51.41%, U with 21.18%, UV with 48.32%, UA with 53.33%, and UP with 48.82% (Figure 5.13). An ANOVA on a binomial regression model showed, that the success of a gesture is dependant on the gesture type ($\chi^2(4) = 679.03, p < 0.001$). Pairwise post-hoc Tukey test revealed that all gesture types significantly differed in success rate. Individual gesture performances were CW with 41.04%, ACW with 55.95%, SL with 5.57%, SR with 21.51%, and V with 99.59%.

Hands off the wheel (HoW) duration was non-normal ($W = 0.949, p < 0.001$). A repeated two-way ANOVA on aligned rank transformed HoW data showed, that condition significantly influences HoW duration ($\chi^2(4) = 4.511, p = 0.001$), as well as gesture family ($\chi^2(4) = 97.658, p < 0.001$); however, there is no mixed effect of both on HoW ($\chi^2(16) = 1.557, p = 0.077$). Post-hoc multiple comparison showed a difference between Ultrasound and every other bimodal combination (U-V: $p = 0.027$, U-UV: $p = 0.016$, U-UA: $p = 0.001$, U-UP: $p = 0.047$), with U impacting HoW duration the least. A *post hoc* multiple comparison showed that Victory gesture impacts HoW duration the least ($p < 0.001$). A Spearman's rank test was run to determine whether there is a correlation between HoW time and successful gesture execution. No significance was found ($S = 2397.9, \rho = 0.077, p = 0.7119$).

Qualitative Data

Analysis of the NASA TLX questionnaire revealed a significant difference in physical demand ($\chi^2(4) = 15.00, p \leqslant 0.01$), with the visual conditions having the highest levels (Figure 5.14). There were no significant differences in the remaining measures: mental demand ($\chi^2(4) = 9.09, p = 0.06$), temporal demand ($\chi^2(4) = 7.23, p = 0.12$), performance ($\chi^2(4) = 8.22, p = 0.08$), effort ($\chi^2(4) = 10.69, p = 0.03$), and frustration ($\chi^2(4) = 5.25, p = 0.26$).

Each participant ranked the feedback types from most to least preferred (Figure 5.14). Analysis of the questionnaire showed that 47.06% of participants preferred Ultrasound-Audio feedback, followed by Ultrasound-Peripheral, Ultrasound-Visual, and Ultrasound feedback. Visual feedback was ranked as least preferred feedback type by 41.17% of the participants.

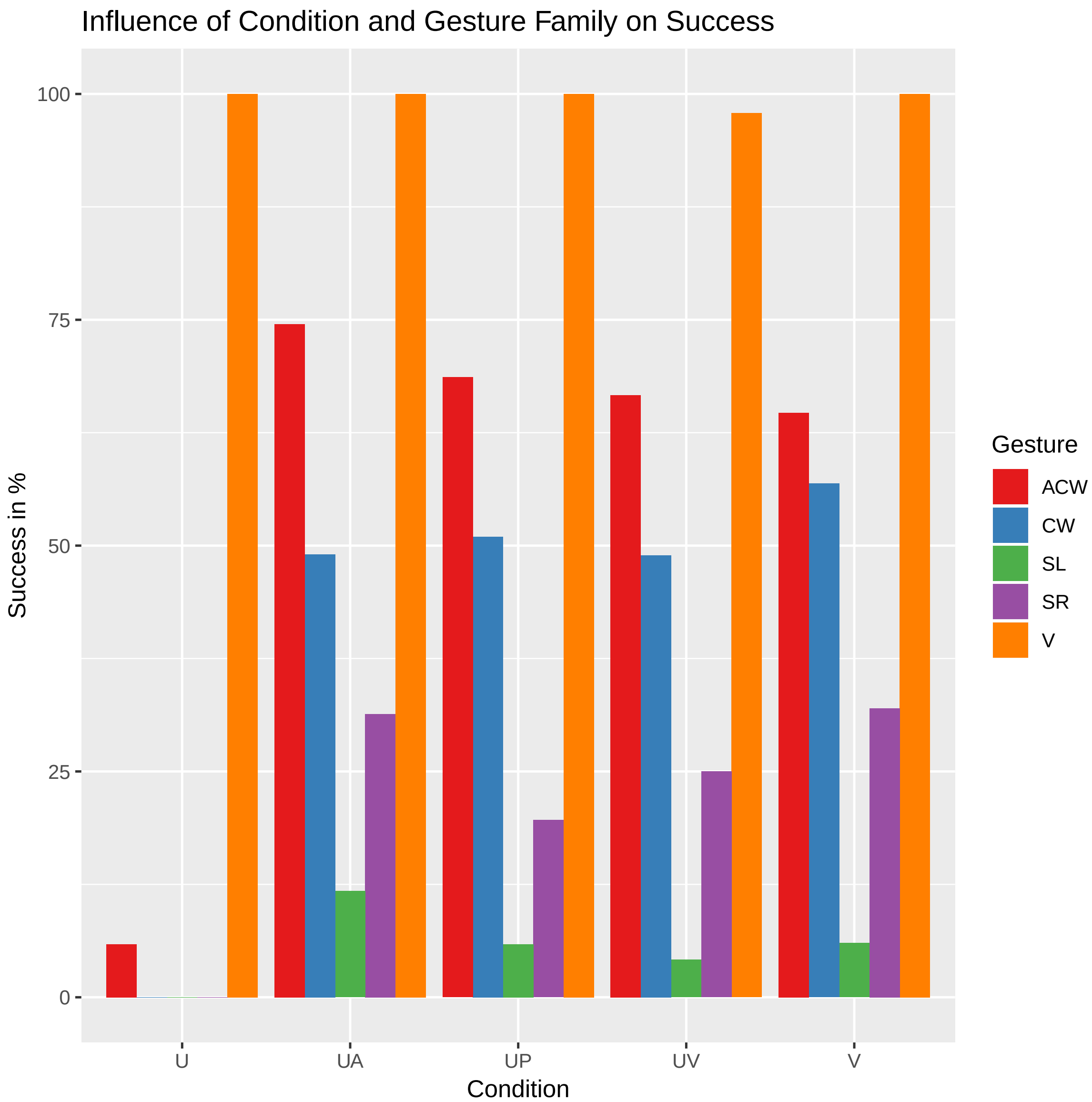


Figure 5.13: Accuracy of gestures across family and feedback condition.

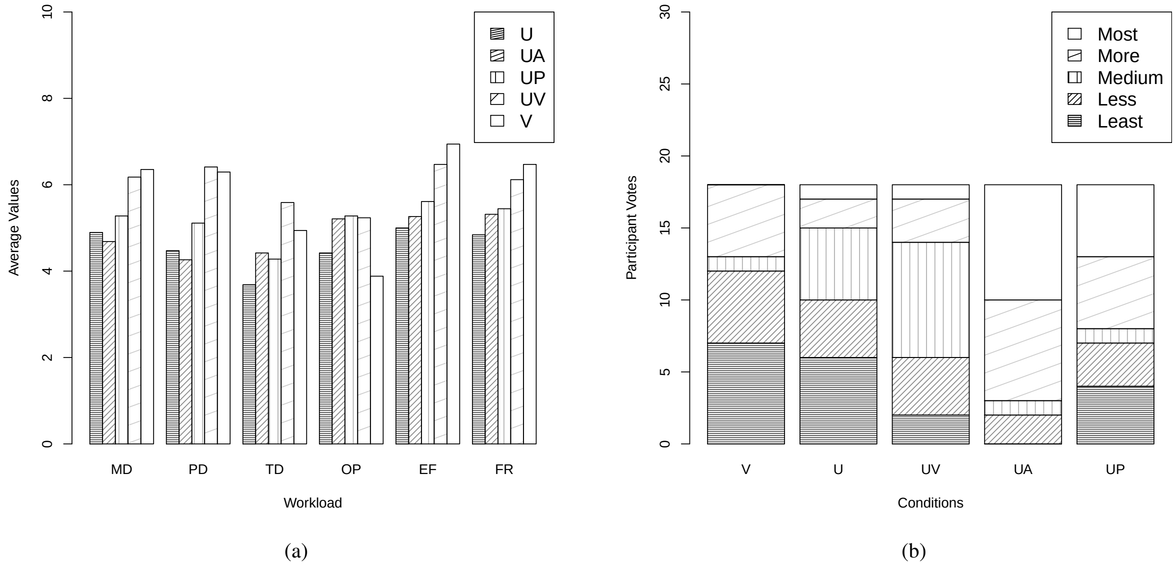


Figure 5.14: Left: Results of the NASA TLX questionnaire (MD: Mental Demand, PD: Physical Demand, TD: Temporal Demand, PE: Performance, EF: Effort, FR: Frustration.). Right: User preferences of bimodal feedback. (V: Visual, U: Ultrasound, UV: Ultrasound-Visual, UA: Ultrasound-Auditory, UP: Ultrasound-Peripheral).

5.4.4 Discussion

In this study, the effects of ultrasound feedback for mid-air gesture interaction on the primary driving task and the secondary gesturing task were investigated.

> **H1** Bimodal ultrasound feedback will improve lane keeping ability compared to unimodal feedback

Hypothesis **H1** was rejected since feedback type had a significant impact on lane deviation, with Ultrasound and Ultrasound-Peripheral Lights affecting the control over the car the least. One potential explanation to this could be that Ultrasound feedback was mentally so demanding that discrimination of stimuli was impossible as a secondary task (see discussion under H4), resulting in participants not caring about how or what they gestured; this lack of execution precision did not have a significant impact on driving performance. The reason to why Ultrasound-Auditory feedback resulted in a significant impact on lane deviation is not clear. It supported gesturing the best and resulted in the highest user acceptance. A future study could look into this.

> **H2** Bimodal ultrasound feedback will improve gesturing ability compared to unimodal feedback

Hypothesis **H2** was rejected since there were significant differences between secondary task performance depending on feedback condition. Gestures were performed best during the bimodal conditions and during the uni-modal Visual condition (Figure 5.13). The high performance rate during the Visual condition is due to participants being familiar with visual feedback in general. The good performance during the bimodal blocks is due to the presentation of redundant information which improves perception of information in mentally demanding situations [43, 44]. Gesture performance during Ultrasound-Audio was highest, which is in accordance with previous findings suggesting that auditory feedback is a suitable alternative for visual feedback when presented to coarse mid-air gestures (Study 5.2 and Study 6 5.3). Unimodal ultrasound feedback resulted in the worst gesture performance of only 21.18% (discussion as to why under Hypothesis 4). However, when ultrasound was presented bimodally, e.g. Ultrasound-Visual, the gesturing performance remained stable compared to Visual feedback and EORT decreased significantly. These findings suggest that ultrasound is useful in a multimodal application for mid-air gesture interaction. If used uni-modally it is more useful in a binary scenario.

> **H3** Non-visual feedback modalities will decrease eyes-off-the-road time compared to visual feedback modalities

The results suggest that providing non-visual, multimodal ultrasound feedback is promising since it reduces EORT significantly compared to visual feedback. Hypothesis **H3** was accepted (Figure 5.12).

> **H4** User workload will be significantly less in the bimodal feedback conditions

Hypothesis **H4** was rejected since there was no significant difference in perceived user workload between the unimodal and bimodal conditions. Despite the fact that uni-modal ultrasound feedback was one of the feedback conditions which caused least mental and temporal demand, least frustration, and generally least effort; quantitative analysis of gesture execution shows that performance was worst (more than 30% worse than Ultrasound-Audio and Visual feedback). An explanation is that participants did not distinguish any feedback patterns provided. For example, the following scenario is likely to have happened: the participant was instructed to swipe left three times but after the first swipe motion the hand "exited" the interaction box area; on second entrance of the hand into the interaction box the system provided a short pulse to the palm; the participant however expected a swipe left motion across the palm but accepted the "entrance" feedback as swipe left feedback. Participant P1 commented this process with "I was never really sure if it was feedback or trying to tell me it is ready". This suggests that the mental effort in distinguishing the haptic messages on the palm were so great — contrary to the NASA TLX results — that participants eventually did not bother to tell them apart. P16 said “hart to identify if move was correct but except that relax drive with less pressur[e]” which supports the hypothesis. Participants accepted any ultrasound feedback at a certain point without caring whether it was the correct one for the executed gesture. This is supported by analysis of hands-off-the-wheel data, which showed that participants used the least time to execute a gesture during Ultrasound feedback. This means, ultrasound stimuli passed the point from being mentally demanding but distinguishable to mentally so demanding that discrimination of stimuli was impossible as a secondary task. This also correlates with the subjective feedback in which P12 commented on the ultrasound feedback “couldn’t always feel the feedback and struggled to tell the difference between the different types of feedback for each motion”. That explains why there is no difference between Visual and Ultrasound-Visual feedback regarding workload. The additional ultrasound modality did not contribute enough to lower it.

The overall low success rate (44.52%) of correct gesture execution led to the belief that the participants might not have noticed or cared enough to match the gesture execution to the instructed commands. Average gesture performances were: CW with 41.04%, ACW with 55.95%, SL with 5.57%, SR with 21.51%, and V with 99.59%. This is likely to be due to the lack of specific consequences of gesturing — i.e. users did not make any actual selections (e.g. select target three) but followed instructions (e.g. swipe left three times). This might have resulted in them believing that any recognised gesture suffices (e.g. 2 left swipes and 1 right swipe). In the beginning of the experiment the participants were instructed to think of the given task as a selection task but that was not enough. This should be taken into consideration when designing gesture experiments.

Interestingly, Victory gesture executions led to high lane deviation. An explanation is that the Victory gesture was the only gesture which participants managed to execute successfully on a consistent basis. It was an easy to perform and easy to recognise gesture, which might have encouraged them execute it correctly, compared to the circular motions and the swiping (as discussed under **H4**).

Finally, regarding user preferences, Visual was ranked least preferred, and Ultrasound second least. Ultrasound-Audio was ranked most preferred followed by Ultrasound-Peripheral. The results of this study suggests that Visual and Ultrasound feedback are not appropriate for in-car usage, unless combined multimodally. If Ultrasound is used uni-modally it is more useful in a binary scenario.

5.4.5 Limitations

The two main limitations in this study were: a) Ultrasound feedback design was perceived as being overly complicated, especially during unimodal feedback, and b) the poor gesture recognition performance of the Leap Motion device. Gesture recognition for circular motions and swiping motions dropped significantly compared to Study 6's average performances ($\sim$ 25% drop for CW, $\sim$ 30% for ACW, $\sim$ 55% for SL, and $\sim$ 20% for SR) even though circle gesture recognition was performed by the same Leap Motion code as in the previous studies 4 - 6. As discussed under hypothesis **H4** (see above), the reason to why this happened might be that participants were frustrated with the sensing system's performance and the lack of specific consequences of poor gesture execution, leading them to no longer try their best.

Another limitation in this study was the relative young age of participants (μ 28.6 σ 6.8). The young age might have facilitated adaptation to this new interaction technique as well as facilitated the perception of the ultrasound feedback. As discussed previously, perception of sensory stimuli degrades with age [167].

5.4.6 Summary

This section contributes multimodal ultrasound feedback techniques for mid-air gesture interaction in driving situations. The aims of this experiment were to: (1) determine the impact of uni- and bimodal ultrasound mid-air gesture feedback on driving safety; (2) investigate which feedback modality supports safe driving during lane change manoeuvres; and (3) analyse which feedback combinations were most preferred by the participants. These aims contributed to answering to the third research question of this thesis:

> **RQ3:** How do *multimodal* mid-air gesture feedback techniques influence driving performance and in-car interaction (*Experiments 5, 6, & 7*)?

and continued to contribute an answer to the fourth research question of this thesis:

> **RQ4:** What effect does multimodal mid-air gesture feedback have on interaction in more *challenging driving* (*Study 6 & 7*)?

Of the four hypotheses identified in Section 5.4.2, all but **H1** were rejected. This study shows that if used unimodally, ultrasound haptics are a useful feedback method for binary mid-air gesture information; these can be a) confirmation that the hand entered the gesture sensing area or b) the system is paying attention to the user and ready to receive input. If used multimodally it significantly reduces eyes-off-the-road time compared to Visual feedback without compromising driving performance or mental demand.

5.5 Conclusions

This chapter investigated the use of multimodal gesture feedback across a number of modalities, to support gesture input while driving. These include Auditory and Cutaneous Push feedback and Visual cues in the periphery. Three experiments were conducted to measure the impact of these feedback modalities on driving performance and efficacy for mid-air gesturing. The motivation for investigating bimodal feedback was to see if redundantly presenting information across two modalities could reduce the workload associated with interaction. Study 4 presented unimodal gesture feedback and found that non-visual output modalities (e.g., Peripheral Lights and Cutaneous Push feedback from the steering wheel) might be low resolution techniques, but they support gesturing without negatively impacting driving or EORT.

The results from Study 5 showed that a combination of low resolution modalities can successfully overcome the shortcomings of each feedback type and provide an additional modality for mid-air gesture feedback. Bimodal combinations of Visual feedback (e.g. Cutaneous Push-Visual) had significantly higher impact on EORT and driving behaviour compared to non-visual modalities, and provide compelling support for its use in driving environments. The results from Study 5 show that workload was similar for the five feedback combinations (Auditory-Visual (baseline), Auditory-Cutaneous Push, Auditory-Peripheral, Cutaneous Push-Peripheral, and Cutaneous Push-Visual), supporting the use of combinations of Audio, Peripheral Visual, and Cutaneous Push feedback. These novel combinations had similar cognitive demand to the baseline Audio-Visual pair, with the advantage of eliminating the need to glance at the console screen.

Study 6 investigated bimodal Auditory-Visual (baseline), Auditory-Cutaneous Push, Auditory-Peripheral, and Cutaneous Push-Peripheral feedback during the Lane Change Task to assess the impact of gesturing and feedback modality on car control during more challenging driving. The LCT is a standard tool used in automotive studies to measure the demands of secondary tasks whilst driving. Therefore, it functioned as a means to measure both, 1) the impact of more challenging driving on gesture interaction, and 2) the impact of mid-air gestures on driving behaviour. The non-visual feedback techniques did not affect driving performance, gaze behaviour, gesturing performance, nor increased workload, suggesting they can support gesture input without increasing distraction and putting safety at risk.

Finally, the use of ultrasound haptic feedback for mid-air gestures in cars has been proposed to provide a sense of control over the user's intended actions and to add touch to a touchless interaction. Study 7 investigated the impact of uni- and bimodal presentation of ultrasound feedback during the Lane Change Task on lane deviation, EORT and perceived workload. The bimodal combinations of ultrasound included Ultrasound, Visual (baseline), Ultrasound-Visual, Ultrasound-Peripheral, and Ultrasound-Auditory. Ultrasound feedback when presented unimodally and bimodally resulted in significantly less EORT compared to visual feedback. The results suggest that non-visual, multimodal ultrasound feedback for mid-air interaction decreases EORT whilst not compromising driving performance nor mental demand.

The results from this chapter provide compelling support for non-visual, bimodal mid-air gesture feedback for in-car interaction. By distributing interaction feedback across multiple modalities, drivers can focus more on the primary task of driving.

5.5.1 Research Question 3

It is important to provide feedback to the driver to keep them informed; however, the feedback should not be cognitively demanding, nor impact driving behaviour. Findings from Studies 5, 6, and 7 suggest that bimodal feedback significantly reduces eyes-off-the-road time compared to Visual feedback without compromising driving performance nor perceived user workload, thus it can potentially reduce crash risks. The outcomes of these experiments are now summarised as recommendations in response to the following research question:

> **RQ3:** How do *multimodal* mid-air gesture feedback techniques influence driving performance and in-car interaction (*Experiments 5, 6, & 7*)?

Mid-air gesture feedback benefits from bimodal feedback. Redundantly presenting information across two modalities reduces EORT and user workload associated with the interaction, whilst supporting the driver in maintaining control over the vehicle. Particularly non-visual feedback combinations have shown to be beneficial for driving environments.

Lower resolution modalities such as Cutaneous Push feedback and Peripheral Lights are optimal for bimodal combinations. They support the driver sufficiently for input without glancing at the input sensor or the car console screen, whilst more importantly, having less impact on the primary driving task and the driver's cognitive load.

Finally, it is particularly important to combine ultrasound haptics with another non-visual modality such as auditory or peripheral lights. As Study 7 showed, unimodal ultrasound feedback functioned as binary information. User perceived it as system attention feedback since attempts to discriminate the presented haptic patterns were too challenging for secondary task information. Ultrasound feedback functioned as redundant confirmation for the other modality, and should be used as such.

5.5.2 Research Question 4

In order to keep distraction from the infotainment system in cars to a minimum, it is necessary to understand their impact on driving performance, especially when driving becomes more challenging. The outcomes of Studies 6 & 7 are now summarised in response to the following research question:

> **RQ4:** What effect does multimodal mid-air gesture feedback have on more *challenging driving* (*Experiments 6 & 7*)?

Even during more challenging driving such as during the Lane Change Task, non-visual feedback combinations caused significantly lower looking away times, and the least impact on driving behaviour (except for Ultrasound-Auditory), without any negative impact on cognitive loads. These results are strong support for bimodal, non-visual feedback for mid-air gestures in cars.

Finally, the results suggest that participants prioritised the lane change task over the gesturing task when both were prompted at the same time. This is in line with previous research suggesting that drivers only perform secondary tasks when the requirements of the driving task are not demanding [250, 251].

5.5.3 Contributions

The research in this chapter makes the following contributions:

- It presents novel multimodal feedback technique for in-car mid-air gesture interaction;
- It investigates their implications for gesture performance, user workload, and driving behaviour during challenging driving;
- It finds that multimodally presented feedback has high user acceptance; especially when combined with auditory feedback.

Chapter 6

Conclusions

6.1 Introduction

This thesis made the following statement in its Introduction:

> This thesis argues that multimodal feedback can support mid-air gesture interaction in cars and reduce eyes-off-the-road time without affecting driving performance, in a simulated driving task. Tactile, auditory, and peripheral visual displays provide gesture systems a variety of ways of presenting information to in-car mid-air gestures, overcoming the need for visual feedback on screens. This thesis presents the design and evaluation of novel feedback techniques which use these modalities to minimise visual information overload without negatively impacting driving performance.

In the chapters that followed, research was presented which supports this statement and aimed at answering this thesis' research questions. Chapter 3 presented Cutaneous Push feedback as an alternative tactile modality for mid-air gesture feedback. It demonstrated its effectiveness in conveying notifications to drivers and contributed a better understanding of tactile messages from the steering wheel. This informed the later use of this modality in supporting mid-air gesture interaction in cars. Chapters 4 and 5 investigated the efficacy of novel uni- and bimodal feedback techniques. The experiments in these chapters found the interaction techniques successful. This chapter will now summarise the research in this thesis, revisit the research questions and discuss how they were addressed and summarised the findings. It also summarises the main contributions, and discusses the limitations of this research and the future work arising from it.

6.2 Research Questions

6.2.1 Research Question RQ1

> How effective is Cutaneous Push feedback from the steering wheel to the driver's palm (*Studies 1, 2, & 3*)?

To answer this question, the research conducted in Chapter 3 presented three experiments which measured participants' recognition performance of *static* and *dynamic* Cutaneous Push patterns, as well as looking at the impact of Cutaneous Push on lateral driving performance and perceived workload. Temporally static Cutaneous Push (i.e. pins protruding and retracting at the same time) showed promise as an alternative modality for in-car notifications through delivering messages discreetly and quickly to the driver. However, static patterns also had limitations regarding complexity and bandwidth. For instance, pattern recognition accuracy decreased with increasing number of pins per pattern, with four being the maximum tested. Additionally, two seconds of display time were necessary for each pattern, allowing drivers enough time for pattern recognition. However, two seconds per notification can elongate interaction duration. Temporally dynamic Cutaneous Push notifications (i.e. pins protrude one after the other) on the other hand, were presented for a total of 500 ms and showed to be an effective means of conveying tactile messages without impacting driving behaviour nor driver workload. Dynamic patterns found high user acceptance; it is important that the users enjoy using an interface, because no matter how safe a particular interface is, it would be irrelevant, if the majority of users do not adopt it.

6.2.2 Research Question RQ2

> How do *unimodal* mid-air gesture feedback techniques influence driving performance and in-car interaction (*Study 4*)?

To answer this question, a study was conducted using unimodal feedback techniques to assist the driver during gesture interaction. Four feedback modalities were presented to the driver: Visual (baseline), Auditory, Peripheral Lights, and Cutaneous Push. The non-visual feedback techniques tested in this study caused the least distraction from the road. As discussed throughout this thesis, it is important to limit visual distraction to avoid increasing the risks of crashes. The lack of visual and physical distraction (turning the head towards the centre console), resulted in participants perceiving non-visual feedback methods as more acceptable in a driving environment. However, the low resolution modalities Cutaneous Push and Peripheral Lights did not support gesture interaction as well as Visual or Auditory feedback.

6.2.3 Research Question RQ3

> How do *multimodal* mid-air gesture feedback techniques influence driving performance and in-car interaction (*Study 5, 6, & 7*)?

To answer this question, three studies were conducted, combining the feedback techniques introduced in the preliminary experiment (Chapter 4) to present bimodal feedback. Results of the three studies have repeatedly shown that non-visual feedback modalities support gesturing in a car without impacting Eyes-Off-the-Road Time (EORT) or perceived workload negatively. Two of the feedback combinations were low resolution: low-fidelity light animations presented in the visual periphery from behind the steering wheel, and cutaneous pressure presented to the driver's palms via pins embedded into the steering wheel. These types of display can only give a limited amount of feedback yet this was enough to support successful gesture input. Such peripheral displays and cutaneous pressure are worth investigating further, to reduce the reliance on a centre console screen that necessitates taking eyes off the road. The peripheral display prototype was half the length of the dashboard, placed behind the steering wheel in front of the driver; the length of the strip can be adapted (increased and decreased). The low resolution modalities Peripheral Lights and Cutaneous Push surpassed their shortcomings when combined and were shown to be very effective feedback techniques for gesture interaction in cars. Non-visual feedback was consistently preferred by users, even during the mid-air ultrasound study (Section 2.5.2), which showed that ultrasound can be a useful method if used multimodally and in binary fashion, for example to confirm the feedback from the other modality.

6.2.4 Research Question RQ4

> What effect does multimodal mid-air gesture feedback have on interaction in more *challenging driving* (*Study 6 & 7*)?

To answer this question, two studies were conducted, using the Lane Change Task to create a *more challenging* driving situation compared to maintaining the vehicle in the middle of a motorway lane, which was used for the simulated driving scenarios in the previous five studies of this thesis. The results showed that even during more challenging driving, non-visual feedback combinations caused significantly lower EORT, and the least impact on driving behaviour (except for Ultrasound-Auditory), without any negative impact on cognitive load. These results are strong support for bimodal, non-visual feedback for mid-air gestures in cars.

6.3 Contributions

This thesis makes novel contributions which inform the design of gesture interaction interfaces in vehicles. Its main contributions are: 1) Cutaneous Push feedback from the steering wheel as a novel feedback modality in driving situations; 2) design and evaluation of unimodal feedback for mid-air gestures using three novel feedback types: a) Peripheral Lights displays; b) Cutaneous Push; and c) Ultrasound tactile feedback; 3) an investigation of the effects of multimodal feedback on mid-air gestures using the above modalities in combination; and 4) an examination of the effects of multimodal mid-air gesture feedback in more challenging simulated driving situations.

6.3.1 Design Recommendations

From the experimental results, design recommendations can be made for multimodal feedback design during mid-air gesture interaction in cars. These are summarised here in Table 6.1; for further discussion see Sections 3.5, 4.6, and 5.5. Some of the findings in this thesis could also be applied to other sensing systems in cars such as speech recognition.

Design Recommendations	Chapter
1. Cutaneous Push notifications are most effective (i.e. good pattern recognition, high user acceptance, no negative impact on driving performance) if the pins are presented temporal *dynamically*. 2. Spatiotemporal static and dynamic Cutaneous Push patterns should be presented to one hand as this results in higher recognition performances than if presented to both hands (e.g. pins on the left hand protrude and retract one after the other). 3. If Cutaneous Push patterns are presented to both hands at the same time, then they should be mirrored. Mirroring patterns across both hands supports perception as it presents information redundantly.	3

Design Recommendations	Chapter
4. The interaction area in a car cockpit is limited, and the system sensing area should be appropriately sized. It needs to be small enough to avoid unintentional user input and large enough to allow for comfortable gesturing. 5. Following the recommendation 4, discreet and static gestures such as Victory are very effective in a driving environment. They should be prioritised over continuous and dynamic gestures such as Swipe. 6. The sensing system needs to be more reliable than the currently available techniques. Robust gesture and intent detection can decrease mental and physical efforts. Studies should use a Wizard of Oz approach to mimic reliable systems.	4
7. Non-visual bimodal feedback techniques are effective ways of communicating *Attention*, *Alignment*, and System State. Non-visual, low resolution modalities can overcome each others' shortcomings if well combined; and thus provide valuable feedback allowing the driver to keep their eyes on the road. 8. It is particularly important to combine ultrasound haptics with another non-visual modality such as auditory or peripheral lights. Unimodal ultrasound feedback functions well as binary information.	5

Table 6.1: The design recommendations presented in each experimental chapter in this thesis.

6.4 Limitations and Future Work

This section will provide suggestions on future work and discuss limitations based on this thesis.

6.4.1 Simulated Driving Task

All studies presented in this thesis were conducted in a laboratory setup using simulated driving scenarios. Although questions regarding the ecological validity of the results can arise, the choice was made because gesture interaction and the presented feedback modalities were novel to most participants. This novelty might have impacted their safety if a real world driving scenario would have been chosen. This limitation is widely accepted in the research community, and most of the cited works in this thesis were also conducted in simulated driving situations. Ng *et al.* [252] found a compromise between real world driving and laboratory study, by sitting the participants on the passenger's seat, while the experimenter drove the car. Designing a study along the lines of Ng *et al.*'s setup would increase the level of realism during the study compared to simulated driving, if the participants are given a primary task, which is equally demanding as driving. Another future investigation could look into introducing traffic participants into the simulated driving environment, or increasing the level of driving demand on the participants by implementing turn-taking.

6.4.2 Trimodal Feedback

A rich body of research has shown that multimodal feedback can be beneficial in a driving environment [253, 42, 254, 14, 255, 256, 207, 44], especially since the context in a driving situation can change quickly. This thesis looked at uni- and bimodal feedback for mid-air gestures. Future work could investigate trimodal feedback, as research has shown it is preferred by drivers [257, 258] over bimodal, and especially over unimodal feedback. Depending on context, trimodal feedback allows the driver to process information from the most appropriate sensory channel [198, 199] and it is perceived as less cognitively demanding compared to unimodal and bimodal feedback. However, modalities have to be combined with consideration, as multimodal feedback can lead to sensory overload if (badly) combined. Krol *et al.* [147] looked at feedback from a wand for remote pointing tasks and found that visual, haptic, and auditory feedback led to sensory overload. Their participants reported to have intentionally discarded the auditory and haptic information as interaction feedback as it was “too much”.

6.4.3 Other Feedback Modalities

The interaction techniques used in this thesis were Visual, Auditory, Peripheral Lights, and Cutaneous Push feedback. Visual and Auditory were chosen as they are commonly used by car manufacturers for mid-air gesture systems. Future steps can investigate the efficacy of vibrotactile feedback from wearables or thermal feedback from the steering wheel [8].

Another direction of future studies could look into a qualitative comparison between vibrotactile steering wheel feedback and Cutaneous Push in terms of urgency, valence, arousal, and message content, as Study 3 participants compared Cutaneous Push to vibration and ranked it as less “stressful” and “urgent”.

6.4.4 Reliability of the Gesture Sensing System

While conducting the research in this thesis, it was found that the Leap motion gesture sensing system was not reliable and caused frustration for the participants. In the long term, frustration can lead to the drivers rejecting mid-air gesture interfaces, regardless of how safe they might be; in the short term, frustration is an emotion which can lead to the inhibition of driving performance and can impact driver safety [106]. The capabilities of the sensing devices need to improve significantly regarding gesture intent and gesture recognition, otherwise users might not accept them. In the presented studies, participants expressed explicit frustration with the swiping motions. The correct performance rates of Swipe gesture were consistently lower than the accuracy of the Circle and Victory gestures. As discussed, the participants might have given up on swiping correctly (such that the system understands) for the sake of swiping as instructed. Future work could investigate the impact of errors (e.g. accidental system activation) on cognitive load, driving performance, and gesturing performance. It is important to asses the effects of unwanted system behaviour as it can divert the driver's attention away from the primary driving task thus decreasing the driver's safety.

6.4.5 Appropriate Set of Gestures for In-car Usage

The aim of this thesis was not to elicit the optimal set of mid-air gestures for driving situations. The gestures used in this study were based on already available gestures in production vehicles. The predominant gestures used in the first study (Study 4) were swiping, circling and the victory gesture. However, over time and with an increasing number of studies, it became clear that the swiping gesture is not ideal for a constrained space like the car cockpit. Discreet and static gestures, like the victory gesture, might be more appropriate for in-car use. Continuous and dynamic gestures such as swiping require more space for execution; as they can require multiple executions, these can impact physical driver fatigue.

6.4.6 Diverse Participant Groups

The participants in the studies were typically young drivers (μ 25.43 σ 7.37). There was no specific focus on recruiting diverse age groups; however this could be a useful future work direction, as age has been shown to cause age related decline in sensory perception [201]. With an increase in the population of older adults around the world, it is important to test the presented feedback modalities across age ranges. Older adults might benefit from multimodal feedback, as it can compensate for age related sensory degradation [167].

6.5 Conclusions

Users need feedback when interacting with a gesture sensing system in cars and this thesis contributes novel interaction techniques which support them. This thesis investigated novel non-visual feedback techniques such as Cutaneous Push from the steering wheel, Peripheral

Lights, and ultrasound haptics. These modalities, combined with each other or with auditory feedback, can be used to support drivers during gesture interaction while allowing them to keep their eyes on the road. The findings showed that these novel techniques were successful in supporting drivers during interaction without increasing visual distraction or perceived workload. Their use in future systems will help drivers gesture more efficiently and more confidently, reducing negative impacts on driving, with the potential to make it safer.

Appendix A

An Appendix

Collected data can be found https://www.dropbox.com/sh/lxb1olh55qn4lod/AADfw3i6St2d-yr0Y1aJfBQka?dl=0 (this is a temporary solution as all data will be moved to the University of Glasgow's Enlighten system). For each study, the data comprises of:

- Code (in Java)
- Questionnaire data
- Collected raw data (anonymous): driving data and gesturing data
- Ethics applications
- Experimental setup pictures
- Analysis Code (in R)
- List of components ordered/used during each study

Other data available on the link are the dissertation, the source files for the dissertation, and figures included in this dissertation.

Bibliography

[1] Continental, https://www.continental-automotive.com/en-gl/Passenger-Cars/Interior/Comfort-Security/Driver-Status/Gesture-Recognition, 2019, [Online; accessed 08/07/2019].

[2] A. Riener, A. Ferscha, F. Bachmair, P. Hagmüller, A. Lemme, D. Muttenthaler, D. Pühringer, H. Rogner, A. Tappe, and F. Weger, "Standardization of the in-car gesture interaction space," *AutoUI*, pp. 14–21, 2013. [Online]. Available: http://dl.acm.org/citation.cfm?doid=2516540.2516544

[3] J. Sterkenburg, S. Landry, and M. Jeon, "Design and evaluation of auditory-supported air gesture controls in vehicles," *Journal on Multimodal User Interfaces*, 2019.

[4] Various, "Leap motion controller," https://www.ultraleap.com/product/leap-motion-controller/, 2017, [Online; accessed 09/03/2020].

[5] E. Freeman, S. Brewster, and V. Lantz, "Towards In-Air Gesture Control of Household Appliances with Limited Displays," pp. 1–4, 2015.

[6] M. Enriquez, O. Afonin, B. Yager, and K. Maclean, "A Pneumatic Tactile Alerting System for the Driving Environment," *Proceedings of the 2001 workshop on Percetive user interfaces - PUI '01*, pp. 1–7, 2001. [Online]. Available: http://portal.acm.org/citation.cfm?doid=971478.971506

[7] B. Mok, M. Johns, S. Yang, and W. Ju, "Reinventing the Wheel?" in *Journal of Vocational Behavior*, 1993.

[8] P. Di Campli San Vito, G. Shakeri, S. Brewster, F. Pollick, E. Brown, L. Skrypchuk, A. Mouzakitis, and A. Mouzaki, "Haptic Navigation Cues on the Steering Wheel." ACM, p. 11. [Online]. Available: https://doi.org/10.1145/3290605.3300440

[9] S. S. Borojeni, T. Wallbaum, W. Heuten, and S. Boll, "Comparing Shape-Changing and Vibro-Tactile Steering Wheels for Take-Over Requests in Highly Automated Driving," in *AutoUI '17*. Oldenburg, Germany: ACM, 2017, pp. 221–225. [Online]. Available: http://doi.acm.org/10.1145/3122986.3123003

[10] N. Medeiros-Ward, J. M. Cooper, A. J. Doxon, D. L. Strayer, and W. R. Provancher, "Bypassing the Bottleneck: The Advantage of Fingertip Shear Feedback for Navigational Cues," pp. 1331–1334, 2010.

[11] S. Hwang and J. H. Ryu, "The haptic steering wheel: Vibro-tactile based navigation for the driving environment," *2010 8th IEEE International Conference on Pervasive Computing and Communications Workshops, PERCOM Workshops 2010*, pp. 660–665, 2010.

[12] B. Sucu and E. Folmer, "Haptic interface for non-visual steering," *Proceedings of the 2013 international conference on Intelligent user interfaces - IUI '13*, p. 427, 2013. [Online]. Available: http://dl.acm.org/citation.cfm?doid=2449396.2449451

[13] ——, "The blind driver challenge: steering using haptic cues," *Proceedings of the 16th international ACM SIGACCESS conference on Computers & accessibility - ASSETS '14*, pp. 3–10, 2014. [Online]. Available: http://dl.acm.org/citation.cfm?doid=2661334.2661357

[14] D. Kern, P. Marshall, E. Hornecker, Y. Rogers, and A. Schmidt, "Enhancing navigation information with tactile output embedded into the steering wheel," vol. 5538 LNCS, no. 1, pp. 42–58, 2009.

[15] F. Beruscha, L. Wang, K. Augsburg, and H. Wandke, "Do drivers steer towards or away from lateral directional vibrations at the steering wheel?" in *Proc. 2nd European Conference on Human Centred Design for Intelligent Transport Systems*, 2010, pp. 227–236.

[16] S. Kim, J. H. Hong, K. A. Li, J. Forlizzi, and A. K. Dey, "Route guidance modality for elder driver navigation," *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, vol. 7319 LNCS, pp. 179–196, 2012.

[17] A. Löcken, H. Müller, W. Heuten, and S. Boll, "AmbiCar: Towards an in-vehicle ambient light display," in *AutoUI*, 2013.

[18] M. Plavšic, M. Duschl, M. Tönnis, H. Bubb, and G. Klinker, "Ergonomic design and evaluation of augmented reality based cautionary warnings for driving assistance in urban environments," *Proceedings of Intl. Ergonomics Assoc*, 2009.

[19] C. Fransson-Hall and A. Kilbom, "Sensitivity of the hand to surface pressure," *Applied Ergonomics*, vol. 24, no. 3, pp. 181–189, 1993.

[20] G. Shakeri, A. Ng, and S. A. Brewster, "Evaluating Haptic Feedback on a Steering Wheel in a Simulated Driving Scenario," in *CHI EA '16*, 2016.

[21] S. E. Lee, E. C. B. Olsen, W. W. Wierwille, and M. Goodman, "A Comprehensive Examination of Naturalistic Lane-Changes 6. Performing Organization Code Unclassified," Tech. Rep., 2004.

[22] P. Green, "Driver distraction, telematics design, and workload managers : safety issues and solutions," *Proc. Int. Congr. Transp. Electron*, pp. 165 –180, 2004.

[23] J. C. Stutts, D. W. Reinfurt, L. Staplin, and E. A. Rodgman, "The role of driver distraction in traffic crashes," 2001. [Online]. Available: www.aaafoundation.org

[24] T. a. Dingus, S. G. Klauer, V. L. Neale, A. Petersen, S. E. Lee, J. Sudweeks, M. a. Perez, J. Hankey, D. Ramsey, S. Gupta, C. Bucher, Z. R. Doerzaph, J. Jermeland, and R. Knipling, "The 100-Car naturalistic driving study phase II - Results of the 100-Car field experiment," *Chart*, no. April, pp. No. HS–810 593, 2006.

[25] T. A. Dingus, F. Guo, S. Lee, J. F. Antin, M. Perez, M. Buchanan-King, and J. Hankey, "Driver crash risk factors and prevalence evaluation using naturalistic driving data," *Proceedings of the National Academy of Sciences*, vol. 113, no. 10, pp. 2636–2641, 3 2016.

[26] M. Rogers, Y. Zhang, D. Kaber, Y. Liang, and S. Gangakhedkar, "The effects of visual and cognitive distraction on driver situation awareness," in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 2011.

[27] VW, "How to make a lot happen with a small gesture," https://www.volkswagen.co.uk/technology/comfort-and-convenience/gesture-control, 2019, [Online; accessed 09/03/2020].

[28] Various, "BMW 7 Series (G11)," https://en.wikipedia.org/wiki/BMW_7_Series_(G11), 2020, [Online; accessed 09/03/2020].

[29] Jaguar, "OPINION: BMW Gesture Control really improves in-car operation," https://media.jaguar.com/news/2017/06/new-jaguar-xf-sportbrake, 2017, [Online; accessed 09/03/2020].

[30] B. Howard, "Hyundai concept car tracks your eyes and hand gestures (not those gestures)," https://www.extremetech.com/extreme/146032-hyundai-concept-car-tracks-your-eyes-and-hand-gestures-not-those-gestures, 2018, [Online; accessed 09/03/2020].

[31] G. Shakeri, J. H. Williamson, and S. Brewster, “Novel Multimodal Feedback Techniques for In-Car Mid-Air Gesture Interaction,” in *AutoUI*, 2017.

[32] P. Green, “Crashes Induced by Driver Information Systems and What Can Be Done to Reduce Them,” *Society of Automotive Engineers Conference Proceedings*, pp. 27–36, 2000.

[33] B. Reimer, B. Mehler, J. Dobres, and J. Coughlin, “The Effects of a Production Level "Voice - Command" Interface on Driver Behavior : Summary Findings on Reported Workload , Physiology , Visual Attention , and Driving Performance,” Massachusetts Institute of Technology, Cambridge, MA., Tech. Rep. 17A, 2013.

[34] E. Freeman, S. Brewster, and V. Lantz, “Do That , There : An Interaction Technique for Addressing In-Air Gesture Systems,” in *CHI*. ACM, 2016, pp. 2319–2331.

[35] P. I. Cornelio Martinez, S. De Pirro, C. T. Vi, and S. Subramanian, “Agency in Mid-air Interfaces,” in *CHI*, 2017.

[36] E. Freeman, S. Brewster, and V. Lantz, “Tactile Feedback for Above-Device Gesture Interfaces: Adding Touch to Touchless Interactions,” in *ICMI*, 2014.

[37] A. Oulasvirta, S. Kim, and B. Lee, “Neuromechanics of a Button Press,” in *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI ’18*, 2018.

[38] K. Harrington, D. R. Large, G. Burnett, and O. Georgiou, “Exploring the Use of Mid-Air Ultrasonic Feedback to Enhance Automotive User Interfaces,” in *AutomotiveUI ’18*, 2018. [Online]. Available: https://doi.org/10.1145/3239060.3239089

[39] T. Carter, S. A. Seah, B. Long, B. Drinkwater, and S. Subramanian, “UltraHaptics: Multi-Point Mid-Air Haptic Feedback for Touch Surfaces,” *UIST*, pp. 505–514, 2013. [Online]. Available: http://dl.acm.org/citation.cfm?id=2501988.2502018

[40] S. Morrison-Smith and J. Ruiz, “Using Audio Cues to Support Motion Gesture Interaction on Mobile Devices,” *CHI’14 Extended Abstracts on Human Factors . . .* , pp. 1621–1626, 2014. [Online]. Available: http://dl.acm.org/citation.cfm?id=2581236

[41] C. D. Wickens, “Multiple resources and mental workload.” *Human factors*, vol. 50, no. 3, pp. 449–455, 2008.

[42] J. B. F. Van Erp and H. a. H. C. Van Veen, “Vibrotactile in-vehicle navigation system,” *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 7, no. 4-5, pp. 247–256, 2004.

[43] C. Ho, H. Z. Tan, and C. Spence, "Using spatial vibrotactile cues to direct visual attention in driving scenes," *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 8, no. 6, pp. 397–412, 2005. [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/S1369847805000525

[44] I. Politis, "The Effects of Modality, Urgency and Message Content on Responses to Multimodal Driver Displays," in *AutomotiveUI 2014 Adjunct Proceedings*, Seattle, WA, USA, pp. 1–5.

[45] A. Farooq, G. Evreinov, R. Raisamo, E. Makinen, T. Nukarinen, and A. A. Majeed, "Developing Novel Multimodal Interaction Techniques for Touchscreen In-Vehicle Infotainment Systems," pp. 32–42, 2014.

[46] J.-H. Lee and C. Spence, "Assessing the benefits of multimodal feedback on dual-task performance under demanding conditions," in *British HCI*, 2008.

[47] C. a. Pickering, K. J. Burnham, and M. J. Richardson, "A research study of hand gesture recognition technologies and applications for human vehicle interaction," *3rd Conf. on Automotive ...*, pp. 1–15, 2007. [Online]. Available: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.135.7688&rep=rep1&type=pdf

[48] M. J. Pitts, L. Skrypchuk, T. Wellings, A. Attridge, and M. a. Williams, "Evaluating user response to in-car haptic feedback touchscreens using the lane change test," *Advances in Human-Computer Interaction*, vol. 2012, 2012.

[49] I. Politis, "Investigating the Effects of Modality , Urgency and Situation on Multimodal Driver Displays," no. May, 2016.

[50] E. Freeman, S. Brewster, and V. Lantz, "Interactive light feedback: Illuminating Above-Device gesture interfaces," in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, vol. 9299, 2015, pp. 478–481.

[51] E. Freeman, "Interaction Techniques with novel multimodal feedback for adressing gesture-sensing systems," Ph.D. dissertation, University of Glasgow, 2015.

[52] V. Bellotti, M. Back, W. K. Edwards, R. E. Grinter, A. Henderson, and C. Lopes, "Making sense of sensing systems: five questions for designers and researchers," in *CHI*, 2002, pp. 415–422. [Online]. Available: http://portal.acm.org/citation.cfm?id=503376.503450

[53] A. Löcken, W. Heuten, and S. Boll, "AutoAmbiCar: Using Ambient Light to Inform Drivers About Intentions of Their Automated Cars Motivation," in *AutoUI*, 2016. [Online]. Available: http://dx.doi.org/10.1145/3004323.3004329

[54] M. A. Regan, J. D. Lee, T. W. Victor, and J. W. Senders, "Driver Distraction and Inattention: A Queuing Theory Approach," in *Driver Distraction and Inattention*. CRC Press, 12 2018, pp. 55–62.

[55] L. Graichen, M. Graichen, and J. F. Krems, "Evaluation of Gesture-Based In-Vehicle Interaction: User Experience and the Potential to Reduce Driver Distraction," *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 2019.

[56] K. M. Bach, M. G. Jaeger, M. B. Skov, and N. G. Thomassen, "Interacting with in-vehicle systems: understanding, measuring, and evaluating attention," *Proceedings of the 23rd British HCI Group Annual Conference on People and Computers: Celebrating People and Technology - BCS-HCI '09*, pp. 453–462, 2009.

[57] N. H. T. S. Administration, "Overview of the National Highway Traffic Safety Administrations Driver Distraction Program," *Washington, DC: National Highway Traffic Safety Administration, Washington*, 2010.

[58] Y. Liang, J. D. Lee, and L. Yekhshatyan, "How Dangerous Is Looking Away From the Road? Algorithms Predict Crash Risk From Glance Patterns in Naturalistic Driving," in *Human Factors*, 2012, pp. 1104–1116.

[59] K. L. Young, M. A. Regan, and J. D. Lee, "Measuring the effects of driver distraction: Direct driving performance methods and measures," in *Driver Distraction: Theory, Effects and Mitigation*, 1st ed., M. A. Regan, J. D. Lee, and K. L. Young, Eds. Australia: CRC Press, 2009, p. 85 105.

[60] M. Regan, T. Victor, and J. Lee, "Driver Distraction and Inattention," in *Driver Distraction and Inattention: Advances in Research and Countermeasures, Volume 1*. SAE, 2013, pp. i–xxiii. [Online]. Available: https://ieeexplore.ieee.org/document/8505197

[61] M. Saifuzzaman, M. M. Haque, Z. Zheng, and S. Washington, "Impact of mobile phone use on car-following behaviour of young drivers," *Accident Analysis and Prevention*, vol. 82, pp. 10–19, 9 2015.

[62] Y. Peng, L. N. Boyle, and S. L. Hallmark, "Driver's lane keeping ability with eyes off road: Insights from a naturalistic study," in *Accident Analysis and Prevention*, 2013.

[63] J. K. Caird, S. M. Simmons, K. Wiley, K. A. Johnston, and W. J. Horrey, "Does Talking on a Cell Phone, With a Passenger, or Dialing Affect Driving Performance? An Updated Systematic Review and Meta-Analysis of Experimental Studies," *Human Factors*, vol. 60, no. 1, pp. 101–133, 2 2018.

[64] F. A. Drews, H. Yazdani, C. N. Godfrey, J. M. Cooper, and D. L. Strayer, "Text messaging during simulated driving," *Human Factors*, vol. 51, no. 5, pp. 762–770, 10 2009.

[65] J. Greenberg, L. Tijerina, R. Curry, B. Artz, L. Cathey, D. Kochhar, K. Kozak, M. Blommer, P. Grant, J. Greenberg, L. Tijerina, R. Curry, B. Artz, L. Cathey, D. Kochhar, K. Kozak, and M. Blommer, "The effects of eight in-vehicle tasks on driver distraction were measured in a large Driver Distraction Evaluation with Event Detection Paradigm," Tech. Rep.

[66] J. Engström, E. Johansson, and J. Östlund, "Effects of visual and cognitive load in real and simulated motorway driving," *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 8, no. 2 SPEC. ISS., pp. 97–120, 2005.

[67] D. B. Kaber, Y. Liang, Y. Zhang, M. L. Rogers, and S. Gangakhedkar, "Driver performance effects of simultaneous visual and cognitive distraction and adaptation behavior," *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 15, no. 5, pp. 491–501, 2012.

[68] Y. Peng and L. N. Boyle, "Driver's adaptive glance behavior to in-vehicle information systems," *Accident Analysis and Prevention*, vol. 85, pp. 93–101, 12 2015.

[69] T. Schaap, A. van der Horst, B. van Arem, and K. Brookhuis, "The Relationship between Driver Distraction and Mental Workload," in *Driver Distraction and Inattention*. CRC Press, 12 2018, pp. 63–80.

[70] J. D. Lee, S. C. Roberts, J. D. Hoffman, and L. S. Angell, "Scrolling and driving: How an MP3 player and its aftermarket controller affect driving performance and visual behavior," *Human Factors*, vol. 54, no. 2, pp. 250–263, 4 2012.

[71] P. Green, "Variations in Task Performance Between Younger and Older Drivers: UMTRI Research on Telematics," Tech. Rep. [Online]. Available: www.umich.edu/~driving,1

[72] ——, "Customer Needs, New Technology, Human Factors, and Driver Science Research for Future Automobiles," *Journal of the Society of Mechanical Engineers*, vol. 99, no. 926, pp. 15–18, 7 2017.

[73] Qun Wu, "An overview of driving distraction measure methods," in *2009 IEEE 10th International Conference on Computer-Aided Industrial Design Conceptual Design*, Nov 2009, pp. 2391–2394.

[74] S. G. Hart and L. E. Staveland, "Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research," in *Human Mental Workload*, ser. Advances in Psychology, P. A. Hancock and N. Meshkati, Eds. North-Holland, 1988, vol. 52, pp. 139 – 183. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0166411508623869

[75] S. Rümelin and A. Butz, "How To Make Large Touch Screens Usable While Driving," *Auto UI 2013*, pp. 48–55, 2013.

[76] M. Geiger, "Berührungslose Bedienung von Infotainment-Systemen im Fahrzeug," Tech. Rep.

[77] K. M. Bach, M. G. Jaeger, M. B. Skov, and M. G. Thomassen, "You can touch, but you can't look: interacting with invehicle systems," in *CHI Conference on Human Factors in Computing Systems*. Florence, Italy: Association for Computing Machinery, 2008.

[78] E. Von Zezschwitz, A. Hang, D. Hausen, R. Haeuslschmid, A. Hoesl, F. Lauber, S. Loehmann, H. Palleis, B. Slawik, S. Stusak, S. Tausch, A. Butz, and H. Hussmann, "Secondary Tasks," 2014.

[79] O. Georgiou, "Haptic In-Vehicle Gesture Controls," in *AutoUI*, Oldenburg, Germany, 2017.

[80] S. Rümelin, T. Gabler, and J. Bellenbaum, "Clicks are in the Air: How to Support the Interaction with Floating Objects through Ultrasonic Feedback," in *AutoUI*, 2017.

[81] H. Jahani, M. Z. Fondazione, B. Kessler, M. Kavakli, and M. Billinghurst, "Towards Optimization of Mid-air Gestures for In-vehicle Interactions," 2017. [Online]. Available: https://doi.org/10.1145/3152771.3152785

[82] D. A. Norman, "The way I see it: Natural user interfaces are not natural," *interactions*, 2010.

[83] D. McNeill, *Gesture and Thought*, 2005.

[84] B. Rime, "The elimination of visible behaviour from social interactions: effects on verbal, nonverbal and interpersonal variables," Tech. Rep., 1982.

[85] R. A. Bolt, "put-that-there voice and gesture at the graphics interface," in *Proceedings of the 7th annual conference on Computer graphics and interactive techniques*, 1980, pp. 262–270.

[86] J. M. Oscillada, "List of gesture controllers for virtual reality," https://virtualrealitytimes.com/2017/02/16/vr-gesture-controllers/, 2017, [Online; accessed 09/03/2020].

[87] Various, “Kinect,” https://en.wikipedia.org/wiki/Kinect, 2017, [Online; accessed 09/03/2020].

[88] ——, “Wii,” https://en.wikipedia.org/wiki/Wii, 2017, [Online; accessed 09/03/2020].

[89] ——, “Air gesture,” https://allaboutgalaxys4.com/galaxy-s4-features-explained/air-gesture/, 2013, [Online; accessed 09/03/2020].

[90] Samsung, “How do i control my tv using gestures?” https://www.samsung.com/au/support/tv-audio-video/using-gesture-control/, 2019, [Online; accessed 09/03/2020].

[91] R. Hutchinson, “ihouse smartfaucet,” https://www.geeky-gadgets.com/ihouse-smartfaucet/, 2009, [Online; accessed 09/03/2020].

[92] J. Pasquero, S. J. Stobbe, and N. Stonehouse, “A Haptic Wristwatch for Eyes-Free Interactions,” *Proceedings of the 2011 annual conference on Human factors in computing systems - CHI ’11*, pp. 3257–3266, 2011. [Online]. Available: http://dl.acm.org/citation.cfm?doid=1978942.1979425

[93] S. C. Lee, B. Li, and T. Starner, “AirTouch: Synchronizing In-air Hand Gesture and On-body Tactile Feedback to Augment Mobile Gesture Interaction,” *2011 15th Annual International Symposium on Wearable Computers*, pp. 3–10, 2011. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5959583

[94] J. Siekmann and W. Wahlster, “Can Haptic Feedback Improve Gesture Recognition in 3D Handwriting Systems?” in *New York*, vol. 5928, 2008, pp. 812–823. [Online]. Available: http://www.springerlink.com/content/v507p254j1561l11/

[95] C. L. Seungyon, L. BoHao, and T. E. Starner, “AirTouch: Mobile Gesture Interaction with Wearable Tactile Displays,” *ISWC Sessions*, no. May, 2011.

[96] Y. Park, J. Kim, and K. Lee, “Effects of auditory feedback on menu selection in hand-gesture interfaces,” *IEEE Multimedia*, vol. 22, no. 1, pp. 32–40, 2015.

[97] R. Kajastila and T. Lokki, “Eyes-free interaction with free-hand gestures and auditory menus,” *International Journal of Human Computer Studies*, 2013.

[98] K. R. May, T. M. Gable, and B. N. Walker, “A Multimodal Air Gesture Interface for In Vehicle Menu Navigation,” in *AutoUI*, 2014, pp. 1–6. [Online]. Available: http://dl.acm.org/citation.cfm?doid=2667239.2667280

[99] D. Wigdor and D. Wixon, *Brave NUI world*, 2011, vol. 36, no. 6.

[100] K. O'Hara, G. Gonzalez, A. Sellen, G. Penney, A. Varnavas, H. Mentis, A. Criminisi, R. Corish, M. Rouncefield, N. Dastur, and T. Carrell, "Touchless interaction in surgery," *Commun. ACM*, vol. 57, no. 1, pp. 70–77, Jan. 2014. [Online]. Available: http://doi.acm.org/10.1145/2541883.2541899

[101] M. K. Bhuyan, D. Ajay Kumar, K. F. MacDorman, and Y. Iwahori, "A novel set of features for continuous hand gesture recognition," *Journal on Multimodal User Interfaces*, vol. 8, no. 4, pp. 333–343, 10 2014.

[102] P. Vogiatzidakis and P. Koutsabasis, "Multimodal Technologies and Interaction Gesture Elicitation Studies for Mid-Air Interaction: A Review," 2018. [Online]. Available: www.mdpi.com/journal/mti

[103] A. Barón and P. Green, "Safety and Usability of Speech Interfaces for In-Vehicle Tasks while Driving: A Brief Literature Review," Tech. Rep., 2006.

[104] T. M. Gable, R. M. May, and B. N. Walker, "Applying Popular Usability Heuristics to Gesture Interaction in the Vehicle," in *AutoUI*, 2014, pp. 1–7. [Online]. Available: http://dl.acm.org/citation.cfm?doid=2667239.2667298

[105] J. Vermeulen, K. Luyten, K. Coninx, N. Marquardt, and J. Bird, "Proxemic Flow: Dynamic Peripheral Floor Visualizations for Revealing and Mediating Large Surface Interactions," Tech. Rep.

[106] M. Jeon, "Emotions and Affect in Human Factors and HumanComputer Interaction Emotions in Driving," 2017.

[107] I. Golod, F. Heidrich, C. Möllering, and M. Ziefle, "Design principles of hand gesture interfaces for microinteractions," in *Proceedings of the 6th International Conference on Designing Pleasurable Products and Interfaces - DPPI '13*, 2013.

[108] J. Sterkenburg, S. Landry, M. Jeon, and J. Johnson, "Towards an in-vehicle sonically-enhanced gesture control interface: a pilot study," in *ICAD*, 2016, pp. 0–3.

[109] E. Freeman, S. Brewster, and V. Lantz, "Illuminating Gesture Interfaces with Interactive Light Feedback Abstract," *NordiCHI*, 2014.

[110] N. Cowan, "The magical number 4 in short term memory. A reconsideration of storage capacity," in *Behavioral and Brain Sciences*, vol. 24, no. 4, 2001, pp. 87–186.

[111] M. Alpern and K. Minardo, "Developing a car gesture interface for use as a secondary task," *CHI EA*, p. 932, 2003. [Online]. Available: http://portal.acm.org/citation.cfm?doid=765891.766078

[112] J. O. Wobbrock, H. H. Aung, B. Rothrock, and B. A. Myers, "Maximizing the guessability of symbolic input," in *CHI '05 Extended Abstracts on Human Factors in Computing Systems*, ser. CHI EA '05. New York, NY, USA: ACM, 2005, pp. 1869–1872. [Online]. Available: http://doi.acm.org/10.1145/1056808.1057043

[113] J. Terken, P. Levy, C. Wang, J. Karjanto, N. M. Yusof, F. Ros, and S. Zwaan, "Gesture-based and haptic interfaces for connected and autonomous driving," in *Advances in Intelligent Systems and Computing*, 2017.

[114] N. Broy, F. Alt, S. Schneegass, and B. Pfleging, "3D Displays in Cars," *Proceedings of the 6th International Conference on Automotive User Interfaces and Interactive Vehicular Applications - AutomotiveUI '14*, pp. 1–9, 2014. [Online]. Available: http://dl.acm.org/citation.cfm?doid=2667317.2667319

[115] R. Sodhi, H. Benko, and A. Wilson, "Lightguide: Projected visualizations for hand movement guidance," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ser. CHI '12. New York, NY, USA: ACM, 2012, pp. 179–188. [Online]. Available: http://doi.acm.org/10.1145/2207676.2207702

[116] F. Roider and K. Raab, "Implementation and evaluation of peripheral light feedback for mid-air gesture interaction in the car," in *2018 14th International Conference on Intelligent Environments (IE)*. IEEE, 2018, pp. 87–90.

[117] A. Kamal, Y. Li, and E. Lank, "Teaching motion gestures via recognizer feedback," in *Proceedings of the 19th International Conference on Intelligent User Interfaces*, ser. IUI '14. New York, NY, USA: ACM, 2014, pp. 73–82. [Online]. Available: http://doi.acm.org/10.1145/2557500.2557521

[118] D. Norman, "The design of everyday things," *Choice Reviews Online*, vol. 51, no. 10, pp. 51–5559, 5 2014.

[119] H. Sacks, "Harvey sacks: lectures on conversation," *Malden, MA: Blackwell Publishing*, 1992.

[120] S. A. G. Wensveen, J. P. Djajadiningrat, and C. J. Overbeeke, "Interaction frogger: a design framework to couple action and function through feedback and feedforward," in *DIS '04 Proceedings of the 5th conference on Designing interactive systems: processes, practices, methods, and techniques*, 2004, pp. 177–184. [Online]. Available: http://dl.acm.org/citation.cfm?id=1013140

[121] D. Brand, K. Büchele, and A. Meschtscherjakov, "Pointing at the HUD." Association for Computing Machinery (ACM), 1 2017, pp. 167–172.

[122] B. N. Walker, A. Nance, and J. Lindsay, "Spearcons: Speech-based earcons improve navigation performance in auditory menus." Georgia Institute of Technology, 2006.

[123] D. R. Large, K. Harrington, G. Burnett, and O. Georgiou, "Feel the noise: Mid-air ultrasound haptics as a novel human-vehicle interaction paradigm," *Applied Ergonomics*, vol. 81, p. 102909, 11 2019. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0003687019301395

[124] D. B. Vo and S. A. Brewster, "Touching the invisible: Localizing ultrasonic haptic cues," in *IEEE World Haptics Conference, WHC 2015*, 2015, pp. 368–373.

[125] J. Williamson, R. Murray-Smith, and S. Hughes, "Shoogle: Excitatory Multimodal Interaction on Mobile Devices," Tech. Rep., 2007.

[126] P. Mistry, P. Maes, and L. Chang, "WUW - wear Ur world." Association for Computing Machinery (ACM), 4 2009, p. 4111.

[127] M. Jeon, B. N. Walker, and T. M. Gable, "Anger effects on driver situation awareness and driving performance," *Presence: Teleoperators and Virtual Environments*, vol. 23, no. 1, pp. 71–89, 2014.

[128] J. Sterkenburg, J. Johnson, S. Landry, and M. Jeon, "Development Tool for Rapid Evaluation of Eyes-free In-vehicle Gesture Controls," in *AutoUI*, 2016. [Online]. Available: http://dx.doi.org/10.1145/3004323.3004357

[129] M. Zobl, R. Nieschulz, M. Geiger, M. Lang, and G. Rigoll, "Gesture components for natural interaction with in-car devices," *The Hand*, pp. 448–459, 2004. [Online]. Available: http://www.mmk.e-technik.tu-muenchen.de/publ/pdf/04/04zob1.pdf

[130] Y. Wu, H. Tan, and J. Zhao, "Exploring aesthetics factors of gesture interaction in vehicles : An empirical study of in-car music player," *Adjunct Proceedings of the 5th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '13)*, pp. 111–112, 2013.

[131] V. Nanjappan, R. Shi, H.-N. Liang, K. K.-T. Lau, Y. Yue, and K. Atkinson, "Towards a Taxonomy for In-Vehicle Interactions Using Wearable Smart Textiles: Insights from a User-Elicitation Study," in *Multimodal Technologies and Interaction*, vol. 3, no. 2, 5 2019, p. 33. [Online]. Available: https://www.mdpi.com/2414-4088/3/2/33

[132] K. R. May, T. M. Gable, and B. N. Walker, "Designing an In-Vehicle Air Gesture Set Using Elicitation Methods." Association for Computing Machinery (ACM), 9 2017, pp. 74–83.

[133] S. Akyol, U. Canzler, K. Bengler, and W. Hahn, "Gesture control for use in automobiles." in *MVA*, 2000, pp. 349–352.

[134] F. Roider and T. Gross, "I See Your Point: Integrating Gaze to Enhance Pointing Gesture Accuracy While Driving," 2018. [Online]. Available: https://doi.org/10.1145/3239060.3239084

[135] R. Jaswal, "Mercedes adds made-in-india gesture control featured in 2019 gle and cla coupe," https://www.drivespark.com/four-wheelers/2019/mercedes-benz-adds-made-in-india-gesture-control-to-the-gle-and-cla-coupe-028627.html, 2019, [Online; accessed 09/03/2020].

[136] M. Chiesa and A. Branciforti, "Experimenting kinect interactions in the car," in *Proceedings of the 4th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, 2012, pp. 49–52.

[137] W. W. Gaver, "Auditory Icons: Using Sound in Computer Interfaces," *Human-Computer Interaction*, vol. 2, no. 2, pp. 167–177, 1986.

[138] M. M. Blattner, D. A. Sumikawa, and R. M. Greenberg, "Earcons and Icons: Their Structure and Common Design Principles," *Human-Computer Interaction*, vol. 4, no. 1, pp. 11–44, 1989.

[139] B. Donmez, L. Ng Boyle, and J. D. Lee, "Differences in Off-Road Glances: Effects on Young Drivers' Performance," *Journal of Transportation and Engineering*, vol. 136, no. 5, pp. 403–409, 2010.

[140] K. Young, P. Salmon, and M. Cornelissen, "Distraction-induced driving error: An on-road examination of the errors made by distracted and undistracted drivers," *Accident; analysis and prevention*, vol. 58, 9 2012.

[141] I. Politis, S. Brewster, and F. Pollick, "Speech Tactons Improve Speech Warnings for Drivers," *Proceedings of the 6th International Conference on Automotive User Interfaces and Interactive Vehicular Applications - AutomotiveUI '14*, pp. 1–8, 2014. [Online]. Available: http://dl.acm.org/citation.cfm?id=2667317.2667318

[142] I. E. González, J. O. Wobbrock, D. H. Chau, A. Faulring, B. a. Myers, and M. G. Hall, "Eyes on the Road , Hands on the Wheel : Thumb-based Interaction Techniques for Input on Steering Wheels," *Screen*, pp. 95–102, 2007. [Online]. Available: http://portal.acm.org/citation.cfm?doid=1268517.1268535

[143] A. Rahman, J. Saboune, and a. El Saddik, "Motion-Path Based in Car Gesture Control of the Multimedia Devices," *Proceedings of the First ACM International Symposium*

on Design and Analysis of Intelligent Vehicular Networks and Applications, pp. 69 – 76, 2011. [Online]. Available: http://dl.acm.org/citation.cfm?id=2069013

[144] J. M. Sullivan and M. L. Buonarosa, "Acquisition, Response, and Error Rates With Three Suites of Collision Warning Sounds." The University of Iowa, 2009, pp. 284–290.

[145] J. B. Van Erp, K. U. Kyung, S. Kassner, J. Carter, S. Brewster, G. Weber, and I. Andrew, "Setting the standards for haptic and tactile interactions: ISO's work," in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, vol. 6192 LNCS, no. PART 2, 2010, pp. 353–358.

[146] K. E. MacLean, "Haptic Interaction Design for Everyday Interfaces," *Reviews of Human Factors and Ergonomics*, vol. 4, no. 1, pp. 149–194, 10 2008.

[147] L. R. Krol, Aliakseyeu, and S. Subramanian, "Haptic feedback in remote pointing," *Proceedings of CHI 2009 Extended Abstracts*, pp. 3763–3768, 2009. [Online]. Available: http://dl.acm.org/citation.cfm?id=1520568

[148] S. Subramanian, C. Gutwin, M. N. M. Sanchez, C. Power, and J. Liu, "Haptic and Tactile Feedback in Directed Movements," *Proceedings of Guidelines On Tactile and Haptic Interactions*, vol. 2, pp. 37–42, 2005. [Online]. Available: http://www.cs.usask.ca/research/research_groups/userlab/GOTHI/Complete Proceedings of GOTHI-05.pdf#page=38

[149] J. C. Craig and K. B. Lyle, "A comparison of tactile spatial sensitivity on the palm and fingerpad," *Perception & psychophysics*, vol. 63, no. 2, pp. 337–347, 2001.

[150] F. Beruscha, K. Augsburg, and D. Manstetten, "Haptic warning signals at the steering wheel: a literature survey regarding lane departure warning systems," *Haptics-e*, vol. 4, no. 5, pp. 1–6, 2011. [Online]. Available: http://www.haptics-e.org/Vol_05/he-v5n1.pdf

[151] J. P. Switkes, E. J. Rossetter, I. A. Coe, and J. C. Gerdes, "Handwheel force feedback for lanekeeping assistance: Combined dynamics and stability," *Journal of Dynamic Systems, Measurement and Control, Transactions of the ASME*, vol. 128, no. 3, pp. 532–542, 9 2006.

[152] J. Pohl and J. Ekmark, "Development of a haptic intervention system for unintended lane departure," in *SAE Technical Papers*, 2003.

[153] G. Shakeri, A. Ng, J. Williamson, and S. Brewster, “Evaluation of haptic patterns on a steering wheel,” in *AutoUI*, 2016.

[154] G. Shakeri, S. Brewster, J. Williamson, and A. Ng, “Evaluating haptic feedback on a steering wheel in a simulated driving scenario,” in *CHI EA ’16*, 2016.

[155] L. Spirkovska, “Summary of tactile user interfaces techniques and systems,” 2005.

[156] C. Ho, V. Santangelo, and C. Spence, “Multisensory warning signals: When spatial correspondence matters,” *Experimental Brain Research*, vol. 195, no. 2, pp. 261–272, 2009.

[157] T. Ferris, S. Hameed, R. Penfold, and N. Rao, “Tactons in multitask environments: The interaction of presentation modality and processing code,” in *Proceedings of the Human Factors and Ergonomics Society*, vol. 3, 2007, pp. 1481–1485.

[158] S. M. Petermeijer, J. C. De Winter, and K. J. Bengler, “Vibrotactile Displays: A Survey with a View on Highly Automated Driving,” pp. 897–907, 4 2016.

[159] S. Brewster and L. M. Brown, “Tactons: Structured Tactile Messages for Non-Visual Information Display,” Tech. Rep., 2004. [Online]. Available: http://eprints.gla.ac.uk/3443/www.dcs.gla.ac.uk/~stephen

[160] “National Highway Traffic Safety Administration Preliminary Statement of Policy Concerning Automated Vehicles,” Tech. Rep.

[161] G. Wilson, T. Carter, S. Subramanian, and S. A. Brewster, “Perception of ultrasonic haptic feedback on the hand,” in *Proceedings of the 32nd annual ACM conference on Human factors in computing systems - CHI ’14*. New York, New York, USA: ACM Press, 2014, pp. 1133–1142.

[162] I. Rutten, L. Van den Bogaert, W. Frier, and D. Geerts, “Invisible Touch:How Identifiable are Mid-Air Haptic Shapes?” in *CHI*, 2019.

[163] T. Howard, G. Gallagher, A. Lécuyer, C. Pacchierotti, and M. Marchal, “Investigating the Recognition of Local Shapes Using Mid-air Ultrasound Haptics,” Tech. Rep.

[164] B. Long, S. A. Seah, T. Carter, and S. Subramanian, “Rendering volumetric haptic shapes in mid-air using ultrasound,” *ACM Transactions on Graphics*, 2014.

[165] W. Frier, D. Ablart, J. Chilles, B. Long, M. Giordano, M. Obrist, and S. Subramanian, “Using spatiotemporal modulation to draw tactile patterns in mid-air,” in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 2018.

[166] G. Shakeri, J. H. Williamson, and S. Brewster, "May the Force Be with You: Ultrasound Haptic Feedback for Mid-Air Gesture Interaction in Cars," 2018. [Online]. Available: https://doi.org/10.1145/3239060.3239081

[167] P. J. Laurienti, J. H. Burdette, J. A. Maldjian, and M. T. Wallace, "Enhanced multisensory integration in older adults," *Neurobiology of Aging*, vol. 27, no. 8, pp. 1155–1163, 8 2006.

[168] M. I. Nikolic and N. B. Sarter, "Peripheral visual feedback: a powerful means of supporting effective attention allocation in event-driven, data-rich environments." *Human factors*, vol. 43, no. 1, pp. 30–38, 2001.

[169] J. Jonides, "Voluntary Versus Automatic Control Over the Mind'S Eye'S Movement," *Attention and performance IX*, vol. 9, pp. 187–203, 1981.

[170] J. Theeuwes, "Exogenous and endogenous control of attention: the effect of visual onsets and offsets," *Perception & Psychophysics*, vol. 49, no. 1, pp. 83–90, 1991.

[171] A. Loecken, W. Heuten, and S. Boll, "Supporting Lane Change Decisions with Ambient Light," *AutoUI '15*, pp. 204–211, 2015.

[172] A. Locken, H. Muller, W. Heuten, and S. Boll, "An experiment on ambient light patterns to support lane change decisions," in *IEEE Intelligent Vehicles Symposium*, 2015.

[173] H. H. van Huysduynen, J. Terken, A. Meschtscherjakov, B. Eggen, and M. Tscheligi, "Ambient Light and its Influence on Driving Experience," in *AutoUI*, 2017.

[174] A. Pauzie, I. . Lescot, C. Des Mobilités, A. Général, and B. . Parc, "Head Up Display in automotive: a new reality for the driver," Tech. Rep.

[175] Y.-C. Liu and M.-H. Wen, "Comparison of head-up display (hud) vs. head-down display (hdd): driving performance of commercial vehicle operators in taiwan," *International Journal of Human-Computer Studies*, vol. 61, no. 5, pp. 679 – 697, 2004. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1071581904000497

[176] G. E. Burnett, "A road-based evaluation of a head-up display for presenting navigation information," in *Proc. of the Tenth International Conference on HumanComputer Interaction (2003)*, 2019, pp. 180–184.

[177] W. J. Horrey, C. D. Wickens, and A. L. Alexander, "The effects of head-up display clutter and in-vehicle display separation on concurrent driving performance," in *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 47, no. 16. SAGE Publications Sage CA: Los Angeles, CA, 2003, pp. 1880–1884.

[178] Y.-C. Liu, "Effects of using head-up display in automobile context on attention demand and driving performance," *Displays*, vol. 24, no. 4-5, pp. 157–165, 2003.

[179] K. W. Gish and L. Staplin, "Human factors aspects of using head up displays in automobiles: A review of the literature, interim report," United States. Joint Program Office for Intelligent Transportation Systems, Tech. Rep., 1995.

[180] M. Smith, J. Streeter, G. Burnett, and J. L. Gabbard, "Visual search tasks." Association for Computing Machinery (ACM), 8 2015, pp. 80–87.

[181] H. J. Oh, S. M. Ko, and Y. G. Ji, "Effects of Superimposition of a Head-Up Display on Driving Performance and Glance Behavior in the Elderly," *International Journal of Human-Computer Interaction*, vol. 32, no. 2, pp. 143–154, 2 2016.

[182] J. H. Iavecchia, H. P. Iavecchia, and S. N. Roscoe, Illiana, "Eye accommodation to head-up virtual images," *Human Factors*, vol. 30, no. 6, pp. 689–702, 1988.

[183] S. N. Roscoe, "The trouble with huds and hmds," *Human Factors*, pp. 30–7, 1987.

[184] L. L. Bossi, N. J. Ward, A. M. Parkes, and P. A. Howarth, "The effect of vision enhancement systems on driver peripheral visual performance." 1997.

[185] D. Dmitrenko, E. Maggioni, and M. Obrist, "I smell trouble: Using multiple scents to convey driving-relevant information," in *Proceedings of the 20th ACM International Conference on Multimodal Interaction*, ser. ICMI 18. New York, NY, USA: Association for Computing Machinery, 2018, p. 234238. [Online]. Available: https://doi.org/10.1145/3242969.3243015

[186] D. Dmitrenko, E. Maggioni, C. T. Vi, and M. Obrist, "What did i sniff? mapping scents onto driving-related messages," in *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, ser. AutomotiveUI 17. New York, NY, USA: Association for Computing Machinery, 2017, p. 154163. [Online]. Available: https://doi.org/10.1145/3122986.3122998

[187] D. Dmitrenko, E. Maggioni, and M. Obrist, "Towards a framework for validating the matching between notifications and scents in olfactory in-car interaction," in *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*, ser. CHI EA 19. New York, NY, USA: Association for Computing Machinery, 2019. [Online]. Available: https://doi.org/10.1145/3290607.3313001

[188] D. Dmitrenko, C. T. Vi, and M. Obrist, "A comparison of scent-delivery devices and their meaningful use for in-car olfactory interaction," in *Proceedings of the 8th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, ser. AutomotiveUI 16. New York, NY, USA: Association for Computing Machinery, 2016, p. 2326. [Online]. Available: https://doi.org/10.1145/3003715.3005464

[189] B. Raudenbush, R. Grayhem, T. Sears, and I. Wilson, "Effects of peppermint and cinnamon odor administration on simulated driving alertness, mood and workload." *North American Journal of Psychology*, vol. 11, no. 2, 2009.

[190] R. A. Baron and M. J. Kalsher, "Effects of a pleasant ambient fragrance on simulated driving performance: the sweet smell of... safety?" *Environment and Behavior*, vol. 30, no. 4, pp. 535–552, 1998.

[191] G. Martin and J. Cooper, "Adding zest to difficult journeys: Odour effects on simulated driving performance," in *The British Psychological Society Annual Conference*, 2007.

[192] C. Oshima, A. Wada, H. Ando, N. Matsuo, S. Abe, and Y. Yanigada, "Improved delivery of olfactory stimukus to keep drivers awake," in *Workshop on DSP for in-Vehicle and Mobile Systems*, 2007.

[193] D. Dmitrenko, E. Maggioni, G. Brianza, B. E. Holthausen, B. N. Walker, and M. Obrist, "Caroma therapy: pleasant scents promote safer driving, better mood, and improved well-being in angry drivers," in *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. ACM, 2020.

[194] U. Castiello, G. M. Zucco, V. Parma, C. Ansuini, and R. Tirindelli, "Cross-modal interactions between olfaction and vision when grasping," *Chemical senses*, vol. 31, no. 7, pp. 665–671, 2006.

[195] L. M. Kay, "Olfactory coding: random scents make sense," *Current Biology*, vol. 21, no. 22, pp. R928–R929, 2011.

[196] A. Seigneuric, K. Durand, T. Jiang, J.-Y. Baudouin, and B. Schaal, "The nose tells it to the eyes: crossmodal associations between olfaction and vision," *Perception*, vol. 39, no. 11, pp. 1541–1554, 2010.

[197] R. W. Holland, M. Hendriks, and H. Aarts, "Smells like clean spirit: Nonconscious effects of scent on cognition and behavior," *Psychological science*, vol. 16, no. 9, pp. 689–693, 2005.

[198] E. Hoggan, T. Kaaresjoa, P. Laitinen, and S. Brewster, “Crossmodal congruence: the look, feel and sound of touchscreen widgets,” 2008.

[199] E. Hoggan, a. Crossan, S. Brewster, and T. Kaaresoja, “Audio or tactile feedback: which modality when?” pp. 2253–2256, 2009. [Online]. Available: http://eprints.gla.ac.uk/43812/

[200] J. Porter, S. Summerskill, and G. Burnett, “BIONIC’eyes-free’design of secondary driving controls,” *Proc. of the Accessible łdots*, 2005. [Online]. Available: http://www.bcs.org/upload/pdf/ewic_ad05_s4paper2.pdf

[201] L. A. Jones and S. J. Lederman, *Human Hand Function*. Oxford UniversityPress, 2006.

[202] Y. Aldien, D. Welcome, S. Rakheja, R. Dong, and P. E. Boileau, “Contact pressure distribution at hand-handle interface: Role of hand forces and handle size,” *International Journal of Industrial Ergonomics*, vol. 35, no. 3, pp. 267–286, 2005.

[203] M. Knibestöl, B. Y. M. Knibestol, and M. Knibestöl, “Stimulus-response functions of slowly adapting mechanoreceptors in the human glabrous skin ara,” *Journal of Physiology*, vol. 245, no. 1, pp. 63–80, 1975.

[204] A. Chan, K. MacLean, and J. McGrenere, “Learning and identifying haptic icons under workload,” *First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics Conference*, 2005.

[205] F. A. Geldard and C. E. Sherrick, “Multiple Cutaneous Stimulation: The Discrimination of Vibratory Patterns”,” vol. 346, no. 1956, pp. 856–857, 1965.

[206] C. D. Chapman, M. D. Heath, D. a. Westwood, and E. a. Roy, “Memory for kinesthetically defined target location: evidence for manual asymmetries.” *Brain and cognition*, vol. 46, no. 1-2, pp. 62–66, 2000.

[207] K. S. Hale and K. M. Stanney, “Design Guidelines from Human Physiological , and Neurological,” *Haptic Rendering - Beyond Visual Computing*, pp. 33–39, 2004.

[208] P. R. Burgess, J. Mei, R. P. Tuckett, K. W. Horch, C. M. Ballinger, and D. a. Poulos, “The neural signal for skin indentation depth. I. Changing indentations.” *The Journal of neuroscience : the official journal of the Society for Neuroscience*, vol. 3, no. 8, pp. 1572–1585, 1983.

[209] A. Gallace, H. Z. Tan, and C. Spence, “Numerosity judgments for tactile stimuli distributed over the body surface,” *Perception*, vol. 35, no. 2, pp. 247–266, 2006.

[210] ——, "The failure to detect tactile change: A tactile analogue of visual change blindness," *Psychonomic bulletin & review*, vol. 13, no. 2, pp. 300–303, 2006.

[211] C. Fransson and J. Winkel, "Hand strength: the influence of grip span and grip type." *Ergonomics*, vol. 34, no. 7, pp. 881–892, 1991.

[212] Logitech, "Logitech g27 racing wheel software and driver setup install download," https://logitechdriversupport.com/logitech-g27-racing-wheel/, 2019, [Online; accessed 09/03/2020].

[213] OpenDS, "Opends 5.0 - open source driving simulation," https://opends.dfki.de/, 2016, [Online; accessed 09/03/2020].

[214] N. Wii, "Wii wheel," https://www.nintendo.com/consumer/downloads/wiiWheelTri.pdf, 2016, [Online; accessed 09/03/2020].

[215] Longacre, "15 inch uncoated black aluminum - drilled - dished," http://www.longacreracing.com/products.aspx?prodid=7620, 2016, [Online; accessed 09/03/2020].

[216] P. A. Green, T. P. Kang, and H. Jeong, "Using an OpenDS Driving Simulator for Car Following: A First Attempt," in *AutomotiveUI 2014 - 6th International Conference on Automotive User Interfaces and Interactive Vehicular Applications, in Cooperation with ACM SIGCHI - Adjunct Proceedings*. Association for Computing Machinery, Inc, 9 2014, pp. 64–69.

[217] J. M. Loomis, "Tactile pattern perception," *Perception*, vol. 10, no. 1, pp. 5–27, 1981.

[218] R. D. Gilson, "Vibrotactile masking: Some spatial and temporal aspects," *Perception & Psychophysics*, vol. 5, no. 3, pp. 176–180, 5 1969.

[219] C. E. Sherrick, "Effects of Double Simultaneous Stimulation of the Skin," Tech. Rep. 1, 1964.

[220] K. Kotovsky and J. C. Bliss, "Tactile Presentation of Visual Information," *IEEE Transactions on Military Electronics*, vol. 7, no. 2, pp. 108–113, 1963.

[221] D. D. Salvucci, "Predicting the effects of in-car interfaces on driver behavior using a cognitive architecture," *Proceedings of the SIGCHI conference on Human factors in computing systems - CHI '01*, pp. 120–127, 2001. [Online]. Available: http://portal.acm.org/citation.cfm?doid=365024.365064

[222] RSOnline, "Push action tubular solenoid, 12.7mm stroke, 24 v dc, 4w," https://uk.rs-online.com/web/p/tubular-solenoid/4317532/, 2016, [Online; RS Stock No. 431-7532; accessed 09/03/2020].

[223] M. Bovenzi, A. J. Welsh, A. Della Vedova, and M. J. Griffin, “Acute effects of force and vibration on finger blood flow,” *Occupational and Environmental Medicine*, vol. 63, no. 2, pp. 84–91, 2 2006.

[224] S. D. Novich and D. M. Eagleman, “Using space and time to encode vibrotactile information: toward an estimate of the skins achievable throughput,” *Experimental Brain Research*, 2015.

[225] K. Myles and M. S. Binseel, “The Tactile Modality : A Review of Tactile Sensitivity and Human Tactile Interfaces,” *Army Research Laboratory*, no. May, pp. 1–27, 2007. [Online]. Available: http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA468389

[226] D. Goldreich, “A Bayesian perceptual model replicates the cutaneous rabbit and other tactile spatiotemporal illusions,” *PLoS ONE*, vol. 2, no. 3, 2007.

[227] I. R. Buck, “Infotainment Interface Design for Automobi les,” *Morris Undergraduate Journal*, vol. 2, no. 2, 2015. [Online]. Available: http://digitalcommons.morris.umn.edu/horizonsAvailableat:http://digitalcommons.morris.umn.edu/horizons/vol2/iss2/1

[228] A. Asif and S. Boll, “Where to turn my car?: comparison of a tactile display and a conventional car navigation system under high load condition,” *Proceedings of the International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI ’10)*, no. AutomotiveUI, pp. 64–71, 2010. [Online]. Available: http://portal.acm.org/citation.cfm?doid=1969773.1969786

[229] Y. Zhang and L. Angell, “Pointing Towards Future Automotive HMIs: The Potential for Gesture Interaction,” *AutoUI*, vol. 22, no. 3, pp. 22–29, 2014. [Online]. Available: http://dl.acm.org/citation.cfm?id=2516540.2516545%5Cnhttp://dl.acm.org/citation.cfm?doid=2516540.2516544%5Cnhttp://portal.acm.org/citation.cfm?doid=1357054.1357233%5Cnhttp://dl.acm.org/citation.cfm?id=1357233%5Cnhttp://portal.acm.org/citation.cfm?doid=135

[230] Landrover, “New discovery sport,” https://www.landrover.com/vehicles/discovery-sport/index.html, 2017, [Online; accessed 09/03/2020].

[231] Audacity, “Free, open source, cross-platform audio software,” https://www.audacityteam.org/, 2016, [Online; accessed 09/03/2020].

[232] Adafruit, “Adafruit neopixel digital rgbw led strip - white pcb 60 led/m,” https://www.adafruit.com/product/2842?length=1, 2016, [Online; accessed 09/03/2020].

[233] T. Baltrusaitis, "Openface - a state-of-the art tool intended for facial landmark detection, head pose estimation, facial action unit recognition, and eye-gaze estimation," https://github.com/TadasBaltrusaitis/OpenFace, 2016, [Online; accessed 09/03/2020].

[234] J. O. Wobbrock, L. Findlater, D. Gergle, and J. J. Higgins, "The Aligned Rank Transform for nonparametric factorial analyses using only ANOVA procedures," in *Conference on Human Factors in Computing Systems - Proceedings*, 2011, pp. 143–146.

[235] J. D. Hincapié-ramos, X. Guo, P. Moghadasian, and P. Irani, "Consumed Endurance : A Metric to Quantify Arm Fatigue of Mid - Air Interactions," pp. 1063–1072, 2014.

[236] K. Katsuragawa, A. Kamal, and E. Lank, "Effect of motion-gesture recognizer error pattern on user workload and behavior," in *Proceedings of the 22Nd International Conference on Intelligent User Interfaces*, ser. IUI '17. New York, NY, USA: ACM, 2017, pp. 439–449. [Online]. Available: http://doi.acm.org/10.1145/3025171.3025234

[237] "BMW's 7-Series 'gesture controls' work pretty well." [Online]. Available: https://eu.usatoday.com/story/money/cars/2016/05/16/bmws-7-series-gesture-controls-work-pretty-well/32613369/

[238] "Look out for Ultrahaptics haptic feedback in new cars this year — TechCrunch." [Online]. Available: https://techcrunch.com/2017/01/03/ultrahaptics-launching/?guccounter=1

[239] E. Freeman, D.-B. Vo, and S. Brewster, "HaptiGlow: Helping Users Position their Hands for Better Mid-Air Gestures and Ultrasound Haptic Feedback," Tech. Rep. [Online]. Available: http://www.adafruit.com/product/1506

[240] C. Eileen Ancman, "Peripherally Located CRTs: Color Perception Limitations," in *NAECON*, 1991.

[241] S. Klauer, T. A. Dingus, V. L. Neale, J. Sudweeks, and D. Ramsey, "The Impact of Driver Inattention On Near-Crash/Crash Risk: An Analysis Using the 100-Car Naturalistic Driving Study Data," *National Highway Traffic Safety Administration*, p. 226, 2006. [Online]. Available: http://hdl.handle.net/10919/55090

[242] LeapMotion, "Leap motion java docs v2.3," https://developer-archive.leapmotion.com/documentation/java/devguide/Leap_Gestures.html, 2017, [Online; accessed 09/03/2020].

[243] T. Kopinski, J. Eberwein, S. Geisler, and U. Handmann, "Touch versus mid-air gesture interfaces in road scenarios-measuring driver performance degradation," in *2016 IEEE*

19th International Conference on Intelligent Transportation Systems (ITSC). IEEE, 2016, pp. 661–666.

[244] L. Tijerina and W. R. Garrott, "A reliability theory approach to estimate the potential effectiveness of a crash avoidance system to support lane change decisions," SAE Technical Paper, Tech. Rep., 1997.

[245] E. C. B. Olsen, S. E. Lee, W. W. Wierwille, and M. J. Goodman, "Analysis of distribution, frequency, and duration of naturalistic lane changes," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 46, no. 22, pp. 1789–1793, 2002. [Online]. Available: https://doi.org/10.1177/154193120204602203

[246] RSeat, "Benq w2000," https://www.projectorpoint.co.uk/benq-w2000.html, 2018, [Online; accessed 09/03/2020].

[247] BenQ, "Rseat gaming seats, cockpits and motion simulators," http://www.rseat.net/rs1-racing-cockpit/rs1-black-black/, 2018, [Online; accessed 09/03/2020].

[248] Ultrahaptics, "Touch development kit user guide," https://developer.ultrahaptics.com/wp-content/uploads/2018/08/TOUCH-Development-Kit-User-Guide.pdf, 2018, [Online; accessed 09/03/2020].

[249] ——, "Ultrahaptics demo at ces 2015 Feeling without touching," "https://www.youtube.com/watch?v=zJK7IF91jmQ", 2015, [Online; accessed 09/03/2020].

[250] B. Metz, A. Landau, and M. Just, "Frequency of secondary tasks in driving results from naturalistic driving data," *Safety Science*, vol. 68, pp. 195 – 203, 2014. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0925753514000873

[251] E. Tivesten and M. Dozza, "Driving context influences drivers' decision to engage in visualmanual phone tasks: Evidence from a naturalistic driving study," *Journal of Safety Research*, vol. 53, pp. 87 – 96, 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0022437515000225

[252] A. Ng and S. Brewster, "An evaluation of touch and pressure-based scrolling and haptic feedback for in-car touchscreens," in *AutomotiveUI 2017 - 9th International ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications, Proceedings*. Association for Computing Machinery, Inc, 9 2017, pp. 11–20.

[253] J. Van Erp and H. Van Veen, "Vibro-tactile information presentation in automobiles," *Proceedings of Eurohaptics*, pp. 99–104, 2001.

[254] K. M. Ba h, M. G. Jæger, M. B. Skov, and N. G. Thomassen, “You can touch, but you can’t look,” *Proceeding of the twenty-sixth annual CHI conference on Human factors in computing systems - CHI ’08*, p. 1139, 2008. [Online]. Available: http://dl.acm.org/citation.cfm?id=1357054.1357233

[255] K. Väänänen-vainio mattila, A. Farooq, G. Evreinov, and R. Raisamo, “User Experience and Expectations of Haptic Feedback in In-Car Interaction,” pp. 248–251, 2014.

[256] O. Halabi, M. B. Hameish, L. Al-Naimi, and A. Al-Kaabi, “A study on the design and effectiveness of tactile feedback in driving simulator,” in *Computer Systems and Applications (AICCSA), 2014 IEEE/ACS 11th International Conference on*, 2014, pp. 742–746.

[257] C. Serafin, R. Heers, M. Tschirhart, C. Ullrich, and C. Ramstein, “User Experience in the U.S. and Germany of In-Vehicle Touch Screens with Integrated Haptic and Auditory Feedback,” in *SAE Technical Paper Series*, vol. 1. SAE International, 7 2010.

[258] M. J. Pitts, M. a. Williams, T. Wellings, and A. Attridge, “Assessing subjective response to haptic feedback in automotive touchscreens,” no. AutomotiveUI, pp. 11–18, 2009. [Online]. Available: http://dx.doi.org/10.1145/1620509.1620512