In-vehicle Touchscreens: Reducing Attentional Demands and Improving Driving Performance

by

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A thesis submitted in partial fulfilment of the requirements for the Degree

of

Doctor of Philosophy

in

Computer Science

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Abstract

Touchscreens are increasingly being used in cars, motorcycles, aircraft, ships, and agricultural machinery to access a wide range of vehicle functions. The primary motivation for incorporating touchscreens in vehicles is that they offer several advantages over physical mechanical controls, including inexpensive to produce, lightweight, low space requirements, design flexibility to handle multiple input/output, quick and easy interface modification, and easy replacement. Touchscreens, on the other hand, lack some features that physical controls have, such as tactile feedback and the same tactile sensations for all controls. The absence of these features on a touchscreen increases visual attentional demands and reduces driving performance, potentially posing a serious safety risk. We have set a primary goal for this research in order to address these issues: Develop new touchscreen interaction methods to improve driving performance by reducing visual attentional demands. We have set three objectives to achieve the primary goal of this research: (1) Examine the design and use of layout-agnostic stencil overlays for in-vehicle touchscreen; (2) To propose in-vehicle dashboard controls interaction framework; (3) To empirically characterise proprioceptive target acquisition accuracy for in-vehicle touchscreens while driving.

Addressing goal (1). Prior stencil based studies suggested that stencil overlays can reduce the need for visual attention on the touchscreen while driving. However, those stencils were Layout-specific with cuts and holes at the underlying touchscreen controls' location. As a result, each stencil could only be used with a single underlying interface. Because contemporary in-vehicle touchscreens are almost always multi-functional, with different interface layouts in different parts of the interface, this restriction is unrealistic for in-vehicle touchscreens. To address the

limitations of previous stencil-based studies. We aimed to design Layout-agnostic stencils. Layout-agnostic means that one stencil can provide tactile guidance to user interface targets regardless of the underlying interface layout, with the term 'layout agnostic' capturing our intention that the stencils should provide tactile guidance to user interface targets regardless of the underlying interface layout. We designed several versions of layout-agnostic stencils iteratively and evaluated them in a simulated driving scenario. Our layout-agnostic stencils failed to reduce visual attentional demands and worsen driving performance, according to the findings.

Addressing goal (2). The failure of objective one prompted us to take a different approach in order to continue working on the research's main goal. In this regard, we have set a new objective, aiming to yield a new understanding. Our stencils failed despite the iterative design process of layout-agnostic stencils, which was supported by prior studies that showed stencils could reduce visual attentional demands. We proposed a "In-vehicle dashboard controls interaction framework" to identify the root causes of layout-agnostic stencils failure. The framework allows for a better understanding of how the driver interacts with the vehicle's dashboard controls. The framework could be used to create new dashboard interaction techniques as well as evaluate current ones.

Addressing goal (3). We used the proposed framework to evaluate the results of layout-agnostic stencils and discovered three knowledge gaps regarding human-dashboard controls interaction while driving. The first knowledge gap was a lack of understanding of how precisely a human can use proprioception to reach a dashboard control. In this regard, we set another goal and conducted an experimental study to assess human proprioceptive abilities to reach dashboard controls in a simulated driving scenario in terms of distance from the body. We empirically characterise proprioceptive target acquisition accuracy for in-vehicle touchscreens while driving based on experimental results. From various distances, we can now determine how accurately humans can reach a specific location on the touchscreen. We proposed touchscreen control sizes (in cm) based on the characterisation. Existing touchscreen user interfaces could be modified to enable eyes-free proprioceptive target acquisition while driving, which would improve touchscreen interaction safety, based on our recommended touchscreen control sizes.

In conclusion, this thesis makes two minor and one major contribution to the field of in-vehicle touchscreen research. The minor contribution is as follows: (1) Better understanding the use of stencil overlays for in-vehicle touchscreens. The following are the major contributions: (2) We proposed a novel framework and it is the first framework in the vehicle dashboard interaction research domain to the best of our knowledge. The proposed framework provides a better understanding of how drivers interact with dashboard controls in vehicles. (3) We proposed a characterisation of the accuracy of proprioceptive target acquisition for in-vehicle touchscreens while driving.

Dedication

I would like to dedicate this thesis to my late father, **Mr. Abdul Qadir Soomro**, who passed away on July 28, 2020, due to COVID-19 illness. He was very interested in this study and wanted to see me graduate as a doctor. He was the one who persuaded me to pursue a doctorate. I wish he was here....

Acknowledgments

I am grateful to Almighty ***ALLAH***, the most beneficent, merciful, and gracious, for His blessings in completing this work successfully.

It is an honour and a pleasure to express my gratitude to Professor Andy Cockburn for his ongoing encouragement, feedback, suggestions, and motivation to complete this research project. It would not be possible without his guidance and motivation. Prof Andy is one of the best supervisors I have ever had.

I also appreciate the Administration and IT department of Computer Science and Software Engineering's kind cooperation and support. I am also grateful to the staff at the Mechanical Engineering Department's 3D printing laboratory for allowing us to use their laboratory and equipment to 3D print stencils, as well as for their insightful feedback.

I am eternally grateful to my beloved wife Paras and my Mother for their love, support, and prayers for my success in this study.

Furthermore, I am grateful to my lab colleagues Ori, Prerna, Dibash, and Haipeng for their encouragement, moral support, and for keeping the lab environment lively throughout this study.

This research was funded by *New Zealand National Science Challenge Grant UOCX1701.*

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Chapter 1

Introduction

Touchscreens are extremely popular and are found in billions of electronic devices. The interaction methods and rich user experience provided by touchscreens are the reasons for their popularity. Touchscreens support a variety of interaction methods, including tapping, dragging, swiping, rotating, and pinching. The touchscreen can be used as both an input and output device. Touchscreens allow users to interact with an object displayed on the screen without using any other input device (such as a mouse). Because users interact with the touchscreen directly with their fingers, these interaction manipulations appear simple and natural. Other input devices, such as a mouse, on the other hand, have indirect contact with a computer. The user moves the mouse with their hand on the surface, and the movement is mapped with the pointer and displayed on the computer screen. Direct interaction with touchscreens provides a rich user experience because users have a direct connection with the computer. Touchscreens' rich user experience has attracted manufacturers from a wide range of consumer electronics industries, resulting in a massive increase in touchscreen use. Touchscreens are now used in smartphones, laptops, tablet computers, home appliances, office appliances, and a variety of other devices.

Touchscreens have also piqued the interest of those in the automotive industry. Touchscreens are used in vehicle control panels such as cars, planes, ships, motorcycles, and agricultural machinery. Because of the introduction of modern electric vehicles, touchscreens in cars have become quite popular and common among these vehicles. Tesla, for example, uses a large touchscreen in their cars and trucks to replace the majority of the physical-mechanical controls on the dashboard. BMW provides access to various vehicle functions via a touchscreen and touch gesture control. The most recent Audi A8 model includes two touchscreens, one for climate control and the other for infotainment and other vehicle functions.

Previously, touchscreens in cars were only used to provide infotainment functions such as media player controls, air-conditioning controls, maps, and so on. Modern in-vehicle touchscreens, on the other hand, provide more than just infotainment controls. We can, for example, adjust the seats, side mirrors, car height, windscreen wipers, auto-pilot controls, and many other things.

The primary reason for incorporating touchscreens into vehicles is that they provide several advantages over mechanical counterparts. Touchscreens, for example, are inexpensive to produce, lightweight, require little space, are simple to replace, and user interfaces can be easily and quickly modified via software updates. Perhaps most importantly, the design flexibility to handle multiple input/output functions on one screen. These benefits may have outweighed the benefits of traditional physical controls such as dials, knobs, sliders, and buttons.

However, touchscreens lack some features found in traditional dashboard controls. Touchscreens, for example, lack tactile feedback and have the same tactile sensations for all controls. The absence of these features increases visual attention, making touchscreens attention-demanding [14], [62], [63], [92]. Physical dashboard controls, on the other hand, have a distinct proprioceptive location relative to the driver, as well as a distinct feel when acquired with finger and thumb. As a result, the driver can learn where the controls are on the dashboard, reach them without looking or glancing, and confirm the acquisition with tactile sensations (e.g., buttons and knobs feels correct if they have a correct relative position to the neighbouring control).

Increased visual attention can result in divided attention, which can lead to distraction. Distraction is defined as anything that diverts attention away from the primary task (for example, driving) [71]. Distraction is a serious safety concern because it directly affects the driver's ability to control the vehicle, resulting in fatal crashes and death [22], [104]. Several studies have found that distracting activities have a negative impact on driving performance [71], [105], [106]. For example, Liang et al. [106] confirmed that visual distraction could delay a driver's response in emerging driving situations, as well as cause drivers to miss road information (such as road signs). As a result, it is critical to address the current issues with in-vehicle touchscreens in order to make them safer to use while driving.

Several tactile and non-tactile feedback techniques have been proposed in previous studies to reduce the attentional demands of in-vehicle touchscreens. Vibrotactile, stencil overlays, and ultrahaptics feedback are examples of tactile techniques. A touchscreen display is vibrated using programmatic control to produce physical sensation when a contact is made with the display in vibrotactile feedback. Stencil overlays are transparent sheets that are mounted as an overlay on top of a touchscreen to help users feel the location of the underlying touchscreen controls. Ultrahaptics uses ultrasound projection directly to the display and on the user's hand to provide multi-point haptic feedback above an interaction surface (mid-air). Each of these feedback techniques has advantages and disadvantages, which are discussed further in the second chapter of this thesis. Among these feedback techniques, stencil overlays could be a quick and easy way to reduce a touchscreen's attentional demands.

Stencil overlays are simple to design and create with a 3D printer, and they do not require any changes to the existing touchscreen or vehicle dashboard. Stencils can be printed in a variety of sizes and installed on any existing touchscreen. Furthermore, stencil overlays do not necessitate the modification of existing touchscreen user interfaces, which means that users can use the touchscreen normally with additional tactile sensations on the controls, potentially reducing attentional demands.

Previous research suggests that stencil overlays can reduce the visual attention demands of in-vehicle touchscreens [13], [15], [43], [47], [92]. However, stencils used in prior studies were layout-specific, with cuts and holes at the underlying touchscreen controls' location. As a result, each stencil could only be used with a single underlying interface. Because touchscreens are almost always multi-functional, with different interface layouts in different parts of the interface, limiting to a single underlying user interface is impractical for general in-vehicle use (e.g., the radio interface layout will be different than for the air-conditioning).

This thesis proposes new touchscreen interaction methods in order to reduce the visual attentional demands of in-vehicle touchscreens while driving. In this regard, we conducted three studies, each of which aimed to yield new insights. To begin, we intend to create and employ layout-agnostic stencils to reduce the attentional demands of in-vehicle touchscreens. The layout-agnostic stencils provide tactile sensations to aid in item selection without requiring visual attention, regardless of the underlying interface's layout. Second, we propose an in-vehicle dashboard controls interaction framework to improve understanding of the driver's interaction with vehicle dashboard controls. We identified several knowledge gaps for in-vehicle dashboard interaction using the framework. One of these gaps is a lack of understanding of the human ability to use proprioception to reach a specific dashboard control. The third study was to empirically characterise proprioceptive target acquisition accuracy for in-vehicle touchscreen while driving.

The subsections that follow present the research aims and objectives of this thesis, as well as the approach used to achieve them. The research contributions of the thesis are then presented, followed by the thesis structure.

1.1 Research Aims and Objectives

The primary goal of this research is to create new interaction methods to reduce visual attentional demands and enable eyes-free interaction with in-vehicle touchscreens while driving. We have set three objectives to achieve the primary goal of this research:

- **Study-I: Examine the design and use of layout agnostic stencil overlays for in-vehicle touchscreen.**

Previous stencil overlays were *layout-specific* and could only be used with one underlying touchscreen user interface. This restriction is unrealistic for a modern touchscreen. As a result, the goal of Study-I was to create and employ **layout-agnostic** stencils for in-vehicle touchscreens in reducing visual attentional demands and improve driving performance. To that end, we conducted an experimental study to evaluate layout-agnostic stencils in a simulated driving scenario.

- **Study-II: A framework to explore the failure of layout-agnostic stencils.**

The findings of Study-I revealed that layout-agnostic stencils did not reduce visual attentional demands and actually worsened driving performance. The failure of Study-I prompted us to take a new path in order to continue working on the primary goal of this research. In this regard, we have set a new goal, aiming to explore the failure of layout-agnostic stencils with a framework.

- **Study-III: To empirically characterise proprioceptive target acquisition accuracy for in-vehicle touchscreens while driving**

We discovered several knowledge gaps for in-vehicle dashboard interaction using the framework proposed in Study-II. One of these gaps was a lack of understanding of the human ability to use proprioception to reach a specific location on a dashboard. In this regard, we have set another goal. The goal of Study-III was to empirically characterise the accuracy of proprioceptive target acquisition for in-vehicle touchscreens while driving. To that end, in a simulated driving scenario, we conducted an experimental study to assess human proprioceptive abilities to reach dashboard controls that are positioned at different distances from the body. We empirically characterise how accurately humans can reach a specific location on the touchscreen from different distances based on the results of Study-III.

1.2 Research Contributions

This thesis has made three research contributions to in-vehicle touchscreens domain, presented as follows:

1. **Better understanding of stencil overlays for in-vehicle touchscreens.** Previous research has shown that layout-specific stencils can reduce the visual demands of in-vehicle touchscreens. However, as previously mentioned, those stencils had limitations. We designed and evaluated layout-agnostic

stencils in this regard, but they failed. We have learned from our experiences that the layout-agnostic stencil designs we used in our study are unlikely to work, and we do not recommend using them.

2. **In-vehicle dashboard control interaction framework.** The proposed framework provides a better understanding of how drivers interact with dashboard controls in vehicles. The proposed framework could help with a variety of in-vehicle touchscreen research studies. First, using in-vehicle controls to better understand low-level human activities while driving could be beneficial. Second, while driving, it could be used to assess in-vehicle dashboard interaction. Third, it may aid car manufacturers and researchers in the development of new systems that are less visually demanding and distracting.

3. **A characterisation of accuracy of proprioceptive target acquisition for in-vehicle touchscreens.** We can determine how accurately humans can reach a specific location on the touchscreen from various distances based on the characterisation. To enable eyes-free proprioceptive target acquisition while driving, we proposed the size (in cm) of touchscreen controls to achieve a certain level of accuracy for various dashboard to body distances. Existing touchscreen user interfaces can be modified to enable eyes-free proprioceptive interaction on the touchscreen based on our recommendations.

1.3 Thesis Structure

There are eight chapters in the thesis. The literature review and related work on in-vehicle touchscreens are presented in Chapter 2. The chapter begins with a discussion of general vehicle distraction issues, followed by an overview of in-vehicle touchscreens, including their benefits and issues in the context of vehicles.

To address these issues, various prior studies are presented, followed by a summary of related work.

Study-I of this research is presented in Chapters 3 and 4, and it examines the design and use of layout agnostic stencil overlays for in-vehicle touchscreens. The third chapter examines the design and method of using layout agnostic stencils. The chapter begins with design goals for layout agnostic stencils, followed by a description of the stencil design process and an experimental setup for evaluating these stencils. The results of the evaluation of agnostic stencils are presented in Chapter 4, followed by a discussion.

Study-II of this research is presented in Chapter 5, which proposes an in-vehicle dashboard controls interaction framework. The framework is presented, followed by an assessment of Study-findings I's and its general applicability to in-vehicle touchscreen research.

Study-III of this research is presented in Chapters 6 and 7, and it aims to empirically characterise proprioceptive target acquisition accuracy for in-vehicle touchscreens while driving. The experimental design and method for evaluating proprioceptive target acquisition for in-vehicle touchscreens are presented in Chapter 6. The results of chapter six, which characterises accuracy for in-vehicle proprioceptive target acquisition, are presented in chapter seven.

The conclusion is presented in Chapter 8, and future work opportunities are discussed.

Chapter 2

Related Work

This chapter is divided into five major sections, beginning with general problems of distraction in vehicles and progressing to the thesis topic, as well as methods and applications to solve distraction in vehicles. The first section discusses distraction, the various types of distraction, and the problems associated with them. The second section discusses in-vehicle touchscreens and their functions, followed by the benefits. The third section discusses touchscreen distraction issues. The fourth section discusses techniques and studies for reducing touchscreen distraction. Finally, a summary of previous work is provided.

2.1 Problems of Distraction in Vehicles

Driving a vehicle involves several human factors, all of which can have an impact on driving performance [70], [71], [105], [106]. One critical factor is driver distraction, which is discussed in this section. Chapter 5 of this thesis discusses other human factors related to driving.

Chapter 5 of this thesis discusses other human factors related to driving.

Driving a vehicle is a difficult task; a driver must process a enormous amount of information available through their senses, memories, and cognitive process [41] in an appropriate and timely manner [71]. Driving can be divided into two categories: primary (driving) and secondary (non-related driving tasks). The most important and critical aspect of driving is the primary task. It entails navigational tasks, vehicle manoeuvres, and maintaining a safe lane position in relation to other external entities such as other vehicles and pedestrians [29]. Talking to another person in the car, operating a mobile phone, or using an infotainment system are examples of secondary tasks (e.g., touchscreen).

Each of these vehicle tasks necessitates some level of attention. Visual, manual, and cognitive attention are all possible. Visual attention is the most important attention property when driving a vehicle. For safe driving, the driver must keep their eyes on the road and avoid missing any external entities that could cause an accident. Secondary tasks, such as using a touchscreen, necessitate multiple forms of attention as well. As a result, the driver must pay attention to both tasks. This is referred to as divided-attention [84]. When both tasks become excessive, one of them must be sacrificed [95]. When the primary task suffers as a result of the secondary task, this is referred to as distraction.

Distraction is defined as anything that diverts attention away from the primary task [71]. Distraction is a serious safety issue because it interferes with the driver's ability to control the vehicle. Several studies have found that distracting activities have a negative impact on driving performance [70], [71], [105], [106]. The United States National Highway Traffic Safety Administration (NHTSA) stated in 2009 that distraction was responsible for 17% of vehicle accidents in the United States, with a total of 3% of these accidents being caused by the distraction of controls integrated with a vehicle [83]. The National Highway Traffic Safety Administration divides distraction into three categories [1].

- **Visual distraction:** occurs when the driver takes eyes-off from the road, such as operating a mobile phone [1].
- **Manual distraction:** occurs when the driver takes their hand-off from steering wheel, such as adjusting seat [1].
- **Cognitive distraction:** occurs when the driver takes their mind-off from driving task, such as talking to other passenger [1].

Distractions of any kind have the potential to increase the risk of accidents. Visual distraction has the highest crash ratio of any of these distractions [48]. Visual distraction can lead to speed variations [77], longer reaction times and poor car control [10], [20], [32], [66], slow response to lead vehicle breaking [19], [107] and an increase in accident rate [18]. Cognitive distraction has also been shown to have an impact on driving behaviour. When a driver is cognitively distracted, they tend to increase or decrease the headway distance to the lead vehicle, which necessitates primarily operational controls (quick acceleration and braking) [87], [88].

2.2 In-vehicle Touchscreens

Touchscreens are used in vehicle control panels such as cars, aircraft, sea vessels, motorcycles, and agricultural machinery. Most modern cars now have a touchscreen that allows access to various vehicle functions. Tesla cars, for example, have a large 17-inch touchscreen, and Tesla trucks have two 17-inch touchscreens that replace the majority of the traditional mechanical components of a dashboard. Touchscreens and touch-sensitive panels are used by BMW and Mercedes to control vehicle functions. Table 2.1 summarises the various functions and features

Table 2.1: Various cars touchscreen functions

<table>
<tr><th>Car Manufacturer</th><th>Level 1 Common Functions</th><th>Level 2 Common Functions</th><th>Manufacturer Specific Functions</th><th>Additional Access Mechanism</th></tr>
<tr><td>BMW</td><td rowspan="7">Media player
Maps
Climate control
Bluetooth connectivity
Application launcher
Settings</td><td rowspan="4">Voice calls
Phone book access
Android Auto
Apple Carplay</td><td>Personal assistant
Voice messages
Weather</td><td>Contact based gesture control
Voice control</td></tr>
<tr><td>Honda</td><td>Emails
Text messages
Third Party Apps</td><td rowspan="6">Voice control</td></tr>
<tr><td>Mercedes</td><td></td></tr>
<tr><td>Nissan</td><td>Voice calls
Facebook
Twitter
TripAdvisor
Car speed warnings</td></tr>
<tr><td>Toyota</td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td>Volkswagen</td></tr>
<tr><td>Tesla</td><td>Voice calls
Phone book access</td><td>Lights adjustment
Autopilot
Web browser
Suspension adjustment
Dashcam
Blindspot
Roof control
Brake Control
Tesla App
Safety and Security functions</td></tr>
</table>

offered by different car manufacturers on their touchscreens. The information presented in Table 2.1 can assist us in understanding what functions various vehicle manufacturers offer, and we can take these functions into account when designing new in-vehicle interfaces and interaction methods.

2.2.1 Advantages of Touchscreens in Vehicles

In-vehicle touchscreens offer many advantages over their physical mechanical counterparts. Major advantages are presented as follows.

- **Ease of modification:** Touchscreens are simple to customise. Over-the-air software (OTA) updates may be used to add or update new features and functions on a touchscreen [13]. Over-the-air updates can also be applied simultaneously on multiple touchscreens, potentially saving time and improving customer satisfaction by eliminating the need for customers to visit a garage for software updates. Adding new features and functions to a traditional mechanical dashboard, on the other hand, may be difficult. Given the number of active vehicles on the road, it may necessitate new hardware and be time-consuming.

- **Design flexibility:** Touchscreens provide greater design flexibility than mechanical dashboard controls. That is, touchscreens can handle multiple input/output functions on a single screen, whereas mechanical counterparts are limited to a few. A single display with multiple functions and a pleasing design aesthetic that may also satisfy customers.

- **Low space requirement:** Touchscreens are also more space efficient than mechanical dashboard controls due to their compact size. A modern vehicle touchscreen of a compact size can perform a variety of functions ranging from media player to vehicle height adjustment (refer to Table 2.1). Because of the limited space on a car dashboard, the number of functions provided by a touchscreen would be difficult to provide with their mechanical counterparts. Having multiple functions on a single screen allows vehicle manufacturers to use that space for other vehicle controls.

- **Light weight:** Touchscreens are also lightweight; a 7" touchscreen may weigh between 230 and 500 grams on average, which is significantly less than mechanical components that perform equivalent functions as a touchscreen. The weight reduction of a dashboard can reduce the overall weight of the vehicle, which may provide additional benefits such as fuel efficiency, braking efficiency, acceleration, and speed [91].

- **Reduced cost:** Touchscreens are also less expensive to manufacture than mechanical dashboard components. When compared to equivalent mechanical dashboard controls, the cost of installing or replacing a touchscreen would be significantly lower.

Despite several advantages over physical dashboard controls, touchscreens have significant limitations, which are discussed in the following section.

2.3 Problems of Touchscreen Distraction

The issue with in-vehicle touchscreens is that they are likely to be visually, manually, and cognitively distracting. For example, the driver takes their eyes off the road to interact with the touchscreen interface, resulting in visual distraction. The driver takes one hand off the wheel to operate the touchscreen, resulting in manual distraction. The driver also takes their attention away from the road to process the visually acquired information from the touchscreen, resulting in cognitive distraction [42]. For example, the driver may be having difficulty understanding and utilising a function.

While driving a vehicle, visual attention is the most important attention property, and touchscreens are visually dependent and may cause distraction [13], [14], [30], [31], [51], [62], [63], [85], [92]. Researchers also calculated the amount of time a driver's gaze is diverted from the road, which can lead to a critical threat, and proposed several guidelines for designing and developing dashboard controls. Green [31] assessed how long a driver spends looking at in-vehicle controls and displays. He proposed that the average duration of a glance not exceed 1.5 seconds. Following Green's recommendations, several other researchers reviewed them and proposed new guidelines for glace duration and task completion time. Summala [90], for example, recommended that a driver's reaction time to an unexpected incident be less than 1.0 second. According to Kujala [49], glances away from a road ahead for more than 1.6 seconds can pose a critical safety risk.

Given the visual attentional demands of in-vehicle touchscreens, this issue must be addressed. Minimizing the need for visual feedback is one way to reduce the visual attentional demands of in-vehicle touchscreens. Visual attention demands can be reduced by using non-visual feedback techniques, such as haptics.

Previous research has proposed a number of techniques for reducing visual attentional demands and enabling eyes-free interaction with in-vehicle touchscreens. Gesture-based techniques (contact and non-contact), touchscreen GUI interaction techniques, secondary displays, stencil overlays, vibrotactile feedback, and ultra-haptics feedback are examples of these.

Prior research has been divided into two sections. We present non-tactile touchscreens to reduce attentional demands in the first section, and tactile sensations techniques to reduce attentional demands in the second section. The related work is presented in the section that follows.

2.4 Methods and Studies of Reducing Touchscreen Distraction

This section describes the related work that has been done to reduce the visual attentional demands of a touchscreen. This section includes research on touchscreen gestures, non-contact mid-air gestures, touchscreen user interfaces, passive tactile sensations, and active tactile sensations.

2.4.1 Contact Based Gesture Techniques

This section contains information about related work on touch-gestures for touchscreens. A touch-gesture is a type of interaction technique in which a human controls the operation of a computer by touching the display with specific gestures such as tap, swipe, pinch, and rotate. Gesture interaction is common in touchscreen devices like smartphones, tablet PCs, laptops, and interactive displays [6], [46], [58], [89], [99]. Prior research has confirmed that gesture interaction reduces attentional load, improves performance, and has the potential to enable eye-to-eye interaction in distracting situations [5].

Several researchers have evaluated gesture-based interaction for in-vehicle touchscreens [3], [14], [23], [60], [95] because it can reduce attentional demands and enable eyes-free interaction. Each of the previous gesture-based studies reported some benefits and drawbacks, which are discussed below.

Previous research found that gesture-based interaction caused participants to make fewer and shorter glances, which helped drivers maintain their attention on the road [3]. However, it was not an entirely eyes-free interaction; drivers needed to take quick glances to support the eye/hand coordination. Swipe gestures are also appropriate for in-vehicle touchscreens, according to research, because they are familiar to users and simple to execute [8]. According to Heikkinen et al. [36], common touch gestures are appropriate for driving contexts because they are simple to perform and do not require precise finger contact with the touchscreen.

Previous research has also shown that gestures are easier to learn than keyboard shortcuts on a computer [3]. However, it was suggested to use a limited set of gestures to make the interaction easier and less cognitively demanding [75]. A large number of gestures may be mentally demanding as well as difficult to execute.

Eren et al. [23] advised against using a large set of gestures; one study proposed gestures as shortcuts for frequently performed operations on a touchscreen, such as navigating through the GUI. These shortcut gestures were task-independent, which means that the same gesture could be used on different states of the GUI, potentially reducing the visual demands of a touchscreen. Colley et al. [14] investigated finger-specific and multi-finger gestures. That is, the system will recognise which finger and how many fingers are in contact with the touchscreen and will execute the function associated with that gesture. The authors reported that gesture interaction techniques do not require precise finger position on the touchscreen (a user can make a gesture anywhere on the touchscreen), and that these gestures are easier to use for eyes-free interaction. Some of the studies that we found interesting are discussed further below; interested readers can read more about these studies as follows.

Bach et al. [3] compared three different touchscreen interaction techniques in early research of in-vehicle touchscreen interaction: direct touch (tap interaction), gestures with one or more fingers, and tactile interaction (physical buttons). The study's goal was to see how these interaction techniques affected primary and secondary task performance while driving. The touchscreen was used for direct touch and gesture-based interaction in the study, and a traditional car stereo was used for tactile interaction. The main task was to use a music player and perform various functions like play/pause, forward/skip, and volume up/down. On a touchscreen, various gesture interactions were used, such as a single tap for play/pause, a swipe left/right for forward/skip, and a swipe up/down for volume up/down functions. The driving task was performed in two scenarios: the first was a controlled real-world driving scenario, and the second was a laboratory-based simulated driving scenario. The findings indicated that gesture interaction can reduce visual attentional demands for a simple task; however, it was not an entirely eyes-free interaction, as participants needed to coordinate their eyes and hands. Direct touch was the quickest interaction technique, but it was also the most visually demanding. The tactile interaction on a traditional car stereo performed worse, with a longer task completion time, more errors, and the highest number of glances.

Burnett et al. [8] investigated the use of swipe gestures on in-vehicle touchscreens. They used different swipe directions to perform different functions, such as increasing the volume of a music player by swiping upwards anywhere on the touchscreen. The research was carried out using a dual-task driving simulation. The participants sat in a Honda Civic SE equipped with a curved LCD screen with a 270° viewing angle. The driving simulation took place on a rural road, with incoming and outgoing traffic in front of and behind the participant's vehicle. Participants had complete control of the vehicle, including steering, acceleration, clutch, and brakes. Participants were taught 32 directional gestures, including commands such as Increase/Decrease, Next/Previous, and Activate/Deactivate. During the experiment, the experimenter would call out the commands verbally, and the participant would have to swipe for the appropriate command. Each swipe gesture should begin in the centre of the touchscreen, which was represented by a green circle (starting point). Overall, 60% of participants (12 out of 20) were able to perform correct directional gestures for various commands, according to the results. A higher success rate was also observed for gestures that participants were already familiar with from previous experience, such as volume increase/decrease commands. The authors concluded that the 60% threshold clearly provides designers with an opportunity to use direction gestures for in-vehicle touchscreens for a variety of functions. The study, however, did not include any eye gaze data. As a result, it remains unclear how direction gestures can reduce visual attentional demands while driving.

Colley et al. [14] introduced a new finger gesture-based in-car touchscreen interaction method. The study's goal was to investigate attentional demand and use gestures to enable eye-free interaction. The authors divided these finger gestures into three categories: standard, finger specific, and multi-finger. The system would determine which finger and gesture a user made on the touchscreen and execute the task accordingly if the user made a gesture anywhere on the screen (Wizard of Oz approached was used in this study). In the study, several in-car user interaction operations were used, such as panning the map, adjusting heating, temperature, and fan speed, and changing radio volume and channels. The study was conducted in a parked car at some locations. The subjects did not drive the car; however, a screen in the car played a video recording of the city. The main input device was a 7-inch touchscreen tablet. To change the interaction menu on the touchscreen, the Wizard-of-Oz approach was used. In general, the study's findings indicate that the *Standard* touch interaction technique was the most appropriate when compared to other finger gesture techniques. When compared to *Standard* and *Multi-finger interactions*, *Finger Specific* interaction has a lower gaze-away time from the primary task. However, there was no statistically significant difference in results demonstrating that finger-specific interaction enabled eyes-free interaction. Subjects also reported that this technique was convenient to use because it allowed for hands-free interaction and required less visual attention.

2.4.2 Non-contact Gesture Techniques

The non-contact (mid-air) gesture interaction for in-vehicle touchscreens is covered in this section. A mid-air gesture is a method of communicating with computers. A user makes gestures in front of a system, which reads the gesture and then performs the appropriate function. The mid-air gesture technique is used in virtual reality headsets [56], [102], games such as Microsoft Kinect [97] and Nintendo Wii [98], and car infotainment systems such as the BMW 7 Series [96].

Prior research has examined mid-air gesture-based interaction techniques for in-vehicle touchscreens in order to reduce visual attentional demands [59], [60], [64], [95]. Mid-air gesture-based interaction showed better driving performance than the touchscreen. The interaction method, however, is slow [60], [95]. The following is some high-level information about important prior studies, which will be explained in considerable detail later. Bar et al. [64] validated the system's ability to recognise hand gestures in a real-world driving situation. According to the study, a reliable vision-based system with 94% accuracy can open up new opportunities for proposed gesture-based interaction for in-vehicle touchscreens. Mid-air gesture interaction has also been tested as a pointing device for touchscreen interaction with auditory feedback, and it has proven to be an effective method for reducing visual attentional demands [95]. The following are some of the studies.

Alpen and Minardo [60] investigated gesture-based interaction for in-vehicle touchscreens and compared it to conventional stereo. On the vehicle windscreen, a gesture interface was displayed in front of the driver. The experiment was carried out in a driving simulator, and subjects used both interactions to perform music player tasks (e.g., find a song and adjust volume). The study's findings suggested that while gesture interaction improved driving performance, it was less accurate and caused more errors when performing music player tasks. The subjects also prefered gesture interaction over traditional stereo because it allowed them to keep their eyes on the road.

Later in 2012, Bar et al. [64] conducted a similar study in which they tested six gestures for in-vehicle touchscreen interaction, as follows: swipe left and right, swipe up and down, and circle clockwise and anti-clockwise. The research seeks to validate how well a vision-based system can interpret hand gestures. They installed a Kinect-based sensor underneath the the touchscreen to read the hand gesture. The touchscreen interface was blank, and no information about the size of the gestures was displayed. The experiment was carried out in a real-world driving scenario, with the driver and front-seat passenger performing these gestures. According to the results, the system was able to detect driver and passenger hand gestures with 94% accuracy. Hand gestures can be used to interact with in-vehicle touchscreen systems, according to the authors, if a reliable vision-based system is used.

Eren et al. [23] proposed mid-air gestures as shortcuts for the frequently used operations on a touchscreen, such as navigation through the menu of a touchscreen. These gestures were also task-independent (not tied to a particular operation on a touchscreen). The research was carried out in a dual-task driving simulation scenario. The primary task was to drive the car; the subjects had to follow a car that was running in front of their vehicle on a straight highway with no curves or bends and no lane changes. The driving simulator was made up of the first half of a Honda Civic car and a curved screen with a 270° viewing angle. Drawing gestures on a touchscreen was the secondary task. The authors assessed ten gestures: square, triangle, star, diamond, infinity, roof, squiggle, spiral, tick, and house. When the subjects drew these gestures on the touchscreen, two levels of feedback were tested: without and with visual feedback. The results revealed a significant difference in eye-gaze data, indicating that subjects relied on visual feedback when it was present. There was no significant difference in drawing accuracy between these gestures. The authors recommend using the tick, roof, squiggle, and triangle gestures because they were the most accurate and easiest to learn. They came to the conclusion that the presence of visual feedback could increase visual attentional demands and that there is no need to provide visual feedback for gesture interaction because it has no effect on gesture accuracy.

Other researchers have experimented with mid-air gestures for touchscreen menu navigation. May et al. [59] investigated the use of mid-air gestures with a touchscreen to navigate through touchscreen menus. A Leap Motion IR hand tracker was used in the study. The research was carried out in a driving simulation scenario. The primary task was to drive the car, and the secondary task was to perform various tasks on a touchscreen using direct touch and gesture-based interaction. The study employed four gestures: select, back, scroll up, and scroll down. The results indicated that the gesture-based interaction results were acceptable according to the NHTSA [1] user interface design guidelines for safe driving. Direct touch, on the other hand, was significantly faster than gesture-based interaction. Furthermore, no significant effect was observed for eye-gaze away time or driving performance.

Sterkenburg et al. [95] experimented with hand gestures as a pointing device for in-vehicle touchscreen interaction. The study evaluated three types of feedback: visual, audio, and visual+audio, and they tested two touchscreen orientations, vertical and horizontal. In the study, a Leap Motion IR-based hand tracker was used. The system directly mapped hand movements captured by the system as a cursor on the touchscreen. The research was carried out in a dual task driving simulation scenario. Subjects were given auditory cues to complete the task on the touchscreen (e.g., *select audio*). According to the findings, audio feedback improved driving and eye gaze performance more than other feedback conditions. There was no difference in task performance for visual feedback based on display orientation. Audio feedback in a vertical orientation, on the other hand, performed poorly. The study concluded that audio feedback displays could only be used safely and effectively while driving; however, this interaction is slower than visual feedback.

2.4.3 Touchscreen GUIs

Several researchers designed and evaluated touchscreen graphical user interfaces that are less visually demanding. In this section, we present two major approaches that have been studied in previous research. The first approach presents various input techniques for scrolling on a touchscreen that could reduce visual attentional demands while browsing through a list, such as searching for a phone number or browsing through music tracks. The second method demonstrates how various graphical user interface layouts can reduce visual attentional demands.

Touchscreens offer numerous functions on a single screen, and to use those functions, users employ various input techniques, one of which is scrolling. Scrolling is the action of moving something up and down on a touchscreen's GUI, such as a contact list. Several touchscreen functions, such as finding a song in a playlist, a contact in a phone book, or searching through a list of GPS application locations, necessitate scrolling. These scrolling tasks can take time and cause distractions while driving [62], [63]. Several researchers have evaluated different input techniques for scrolling on a touchscreen [50], [54], [62], [63].

So far, several scrolling techniques for touchscreens have been investigated, including swipe, kinetic, scrolling with on-screen buttons, scrolling with a physical dial/knob, and scrolling with pressure-based buttons. Swipe scrolling occurs when a user swipes his or her finger up or down to move the list, and the list stops immediately when the finger is no longer in contact with the touchscreen. Kinetic scrolling is similar to swiping, but the list stops slowly depending on the speed of the swipe. Scrolling with on-screen buttons is accomplished by pressing the up/down buttons. A physical dial/knob is linked to a touchscreen; rotating the knob causes the list on the touchscreen to move. Finally, pressure-sensitive buttons are attached to a touchscreen; pressing the buttons scrolls the list. The following are some studies done.

Kujala [50] conducted an experimental study on a touchscreen to compare three different scrolling techniques (on screen buttons, swipe, and kinetic) to evaluate input type and understand driver distraction. On-screen buttons were two buttons on the touchscreen that could be pressed to move the list up and down. Swipe and kinetic were both performed on the list. The experiment was carried out in a simulation environment on a standardised lab setup with a fixed-based medium-fidelity driving simulator. The simulation was displayed on a large screen, and two small 22-inch displays were mounted on the sides to simulate actual driving. To capture touch input, a 'iPhone 3G' mobile phone was used. The study results show a significant difference in visual attentional demands, with kinetic scrolling requiring more visual attention, increased workload, and worse path deviation than swipe and on-screen buttons. The results showed that when using swiping interfaces, the speed decreased.

Lasch and Kujala [54] evaluated the same three scrolling techniques, but they altered the experiment design. The number of items displayed on-screen per page has been increased by the authors, and subjects have been given the option of selecting mobile device orientation (portrait and landscape). In the study, a Nokia E7 touchscreen mobile phone was used to collect touch input. The experiment was carried out in the same manner as previously discussed. When compared to on-screen buttons and kinetic, swipe caused fewer distractions and shorter glance duration at touchscreen. In all three conditions, there was no statistically significant difference in error rate. In addition to these findings, there was no significant difference in any of the measures used in this study based on device orientation.

The study's key finding was that scrolling tasks required more visual attention and did not meet the recommendations from NHTSA [1]; minimum glace time of 2 seconds.

Ng and Bewster [62] conducted an experimental study to investigate various list-based scrolling techniques. The following scrolling techniques were used in the study: direct scrolling, pressure-based buttons, and touchscreen on-screen buttons. Direct scrolling was accomplished by swiping up and down on the touchscreen to move through the list. Pressure-based scrolling was accomplished by applying pressure to physical buttons (external device was installed). The scrolling tasks were designed to replicate the experience of browsing music and contacts on a touchscreen. The study also investigated the effect of size by using two different sizes of menus (4mm and 8mm). The experiment was conducted out in a non-driving in-car setup, with a mock steering wheel mounted on the front passenger seat to simulate the driving experience. According to the study's findings, direct touch was the least accurate method of scrolling when compared to on-screen buttons and pressure-based scrolling. Direct touch, on the other hand, was the fastest of all input conditions, taking half the time of the others. The large size of the menu items improved the touchscreen's accuracy. The study's findings were comprehensive because no other important measures (path deviation, glance count, and gaze-away time) were reported in the findings.

Another study was conducted by Ng et al. [63] to investigate the effect of different scrolling input techniques on visual distraction while driving. The inputs were the same as in their previous study [62]. Four scrolling input techniques were evaluated, as shown in Figure 2.1: external pressure-based buttons connected to the touchscreen, a physical dial connected to the touchscreen, swipe, and on-screen buttons. Vibrotactile feedback was also used to evaluate physical dials and pressure-based buttons. The experiments were conducted out in a dual-task setup, with all four approaches employing list-based targets. The study was conducted out in a real car; subjects drove 56 kilometres, including town roads, carriageways, and highways. The amount of time spent looking away from the primary task was also recorded. The authors did not collect any driving performance data, but they did observe the effects of input techniques on driving performance. In all four conditions, there was no significant difference in target accuracy or mean glance time. However, there was a significant difference in selection time and glance count, with Swipe being the fastest and requiring the fewest glances. There was no significant difference in the results with vibrotactile feedback. However, the number of glances was low, and accuracy improved by 4%.

Figure 2.1: Pressure based buttons, physical dial and touchscreen [63]

The second approach studied in prior studies is on the layout of graphical user interface of touchscreen, focusing on factors such as the size of touchscreen controls, location on the touchscreen, and the number of touchscreen items (controls). These are critical design parameters because they are likely to influence driving performance while using an in-vehicle touchscreen. Several recommendations for the minimum size of a touchscreen button have been made (for example, 19mm [39] and 22mm [37]). Essentially, the touchscreen controls should be at least the size of an adult human fingertip (typically 16-20mm in diameter) [17]. These recommendations were primarily made for non-driving and single task attention scenarios, in which the user could dedicate all of his or her attention to a single task. These recommendations may not be appropriate for in-vehicle touchscreens, as using a touchscreen while driving creates divided attention.

There are several guidelines and standards in the automotive industry for designing mechanical dashboard controls such as buttons, knobs, and sliders [2], [82], [86]. However, similar guidelines for in-vehicle touchscreen controls are not yet available [24], [26], [35]. In this regard, a large number of researchers have evaluated design factors for in-vehicle touchscreen controls while driving. Several researchers have evaluated the effects of different touchscreen control sizes on driving performance and visual attentional demands [21], [22], [26], [45], [52]. The following are some studies done.

Rumelin and Butz [75] evaluated three different interaction techniques on a large 17" touchscreen. Proprioception interaction, haptic perception, and positioned-independent touch gestures were the interaction techniques used. SpaceTouch, which consisted of touch buttons, was used for proprioception interaction (60 $\times$ 78 mm in size). KnobTouch was used to describe the haptic perception; a physical non-active knob was mounted on the touchscreen and served as an anchor to interact with the touchscreen button (64 x 70 mm) while also providing tactile sensations. SwipeTouch was the name given to touch gesture interaction. The research was conducted in a dual-task driving simulation setup. The main task was to follow a vehicle travelling at 100 km/h on a two-lane road. The secondary task was to use a music player to perform functions such as play/pause. According to the study's findings, SpaceTouch was faster and easier to interact with. However, the size of the controls on SpaceTouch was still insufficient to allow for completely eyes-free interaction. SwipeTouch was the least visually demanding and allows for eyes-free interaction; however, it can only be used for a limited number of functions. Furthermore, no statistically significant difference in driving performance was observed across all interaction techniques.

Kim et al. [45] evaluated five different sizes of touchscreen controls: 7.5mm, 12.5mm, 17.5mm, 22.5mm, and 27.5mm. The study's goal was to look into the impact of various touch button sizes on driving safety. The research was conducted in a dual-task simulation setup. The main objective was to drive the car on a three-lane highway. A large 17" touchscreen was used for the secondary task. The subjects were required to enter numbers using the numeric keypad; the size of the numeric keys is shown above. According to the study findings, key size is correlated with driving and task completion performance; with large key size (lowest mean path deviation, lowest speed variation, least glances and gaze-away time, and lowest task completion time) was observed. These results, however, were based on a simple driving task: a straight highway with no turns or incoming traffic. If the driving task had been moderate or difficult, the results could have been very different.

Eren et al. [21] investigated various sizes, location, and contrast on touchscreen buttons that could be used with no visual demands. The button sizes were small (2×2cm), medium (6×6cm), large (10×10cm), and xlarge (14×14cm), and they were tested in nine different locations on the touchscreen. The research was conducted in a dual-task driving simulation setup. The main objective was to drive the car on a straight three-lane highway with no bends or turns. The subjects were instructed to follow a car at a speed ranging from 60 to 70 miles per hour. The secondary task was to choose a button from the touchscreen; only one button was visible at a time. The size, location, and contrast level were counterbalanced for each participant. According to the study findings, the xlarge button was less visually demanding and required fewer screen glances than the small buttons. There was no noticeable impact of button location or contrast; however, the small button near the bottom right corner of the touchscreen was noticeably distracting.

Eren et al. [22] investigated how large touchscreen controls must be in order to provide complete eyes-free operation with peripheral vision and muscle memory. The authors compared three different sizes of touchscreen controls in this regard (6x6, 10x10 and 14x14 cm). The study was conducted in a non-driving simulation setup, in which subjects sat in the car but did not drive it. A static image of the driving scenario was displayed on a curved screen with a viewing angle of 270°. The subjects had to select square-shaped buttons on the touchscreen while pretending to drive the car. According to the findings of the study, peripheral vision may help to reduce attentional demands. However, no such findings were presented to back up this claim. The study only presented task completion time results, implying that task completion time was short on large buttons. Other results were not presented in the paper, such as target selection accuracy (mean miss distance from the target) and visual attention (eyes-gaze direction).

Large et al. [52] conducted a series of experiments to develop a model that predicts the visual demands (total glance time, mean glance duration, and number of glances) for in-vehicle touchscreens while taking into account different button sizes and the number of buttons on the screen. The experiment was conducted in a dual-task driving simulation environment. The primary task was to drive the car on a three-lane UK highway while following the car in front of it. An overhead projector was used to display the driving task, which covered a 270° field of view. The secondary task was to use the touchscreen to locate and select targets. The touchscreen targets were shown in two different orders: unstructured and structured (alphabetically, row-by-row). The study used the model to predict values and compared them to typical experimental values (such as total glance time, mean glance duration, and the number of glances). According to the findings of the study, the proposed model can predict visual behaviour associated with in-vehicle touchscreens while driving.

Feng et al. [26] investigated different sizes and numbers of touchscreen buttons to analyse visual demands while driving and not driving. The following button sizes were evaluated: small (14mm), medium (24mm), and large (33mm). Each of these sizes had three levels of quantity in a grid format: 2×2 (4 buttons), 2×4 (8 buttons), and 3×5 (15 buttons). The research was conducted out in a dual-task driving simulation setup. The participants were instructed to drive a car on a two-way highway at a speed of 60-70mph while staying in the left lane. There were no other vehicles on the road during the simulation, which was a square loop. The secondary task involved selecting a cue of buttons on a touchscreen. Each of these objectives was evaluated both with and without driving. According to the findings of the study, the greater the number of items (3×5, 15 buttons), the longer the task completion time, the longer the gaze-away time, and the more glances required to complete the task with and without driving. According to the findings of the study, the number of buttons on the screen has an increasing effect on task completion time, gaze-away time, and glances.

2.4.4 Passive Tactile Sensations

Buxton proposed in early research that physical templates (shown in Figure 2.2) could be placed on a touchscreen to allow the user to interact with the touchscreen while keeping their eyes on the primary display in dual attention tasks [9]. This method has caught the interest of researchers working to improve touchscreen interaction methods for visually impaired people [27], [40], [43]. Physical augmentations for in-vehicle touchscreen interactions have also been evaluated in recent years in order to reduce attentional demands. Recent in-vehicle touchscreen studies have confirmed that physical augmentations can reduce attentional demands and enable eyes-free interaction while driving [13], [15], [61].

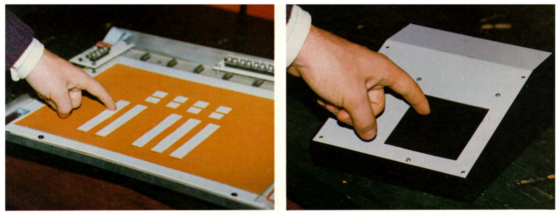


Figure 2.2: Physical templates proposed by Buxton [9]

Physical augmentations can be static or dynamic. Static augmentations are based on stencils, have consistent physical properties (e.g., shape, texture, visibility, and tactile sensations), and do not require any additional equipment to function. Dynamic augmentations are made of gel-based materials, which can change their physical properties and require additional electrical/mechanical components to function. Both types of augmentations have been proposed and evaluated in previous touchscreen-based studies. The following are previous studies on static augmentations.

As shown in Figure 2.3, Robert Kincaid [47] introduced tactile guidelines: a transparent overlay for touchscreens. The purpose of the study was to investigate the use of tactile guidelines to provide tactile sensations for touchscreen controls on measurement instruments. Subjects were asked to perform various interactions on a touchscreen with and without an overlay, such as button presses, sliders, and dials. The study's findings indicated that the overlays could reduce task completion time. The authors also stated that overlays could reduce visual attentional demands; however, no eye-gaze data was presented to back up this claim. Furthermore, large cutouts were ineffective at providing tactile sensations unless the user interacted with the control around the edge.

A similar study was conducted by Colley et al. [15] to investigate the use of overlay (perspex sheet) for in-vehicle touchscreens to reduce unintentional screen

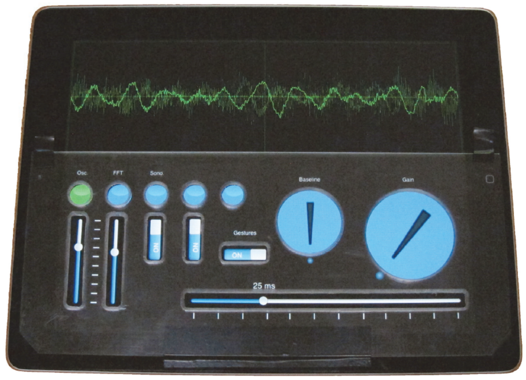


Figure 2.3: Tactile guidelines proposed by Robert Kincaid [47]

touch and enable eye-free interaction. The perspex sheet had holes and channels that were designed with the underlying screen UI operations in mind. The transparent Perspex sheet also allowed non-interactive widgets to be displayed across the entire touch screen. The study was conducted out in a single task non-driving scenario. Two 10.1" touchscreen Samsung tablets were used, one for input and the other for output. The output screen was an exact replication of the input screen and was placed 1.2m in front of subjects to simulate the driver's operation of a car or farm tractor, where the driver's gaze is directed towards the external environment rather than the controls. The evaluation task required four sliders to be moved to the target position highlighted in red on the UI, as shown in Figure 2.4. Subjects completed 13 tasks with and without the overlay and rated each condition on a scale of one to ten. The study's findings show that there was no significant difference in task completion time between the two display conditions. When the overlay was installed, subjects spent more time interacting with the touchscreen. Overlay was rated as easier to interact with by participants. Some users, however, reported distractions and discomforts while operating. The authors came to the conclusion that overlays have the potential to improve touchscreen interaction while also reducing visual attentional demands.

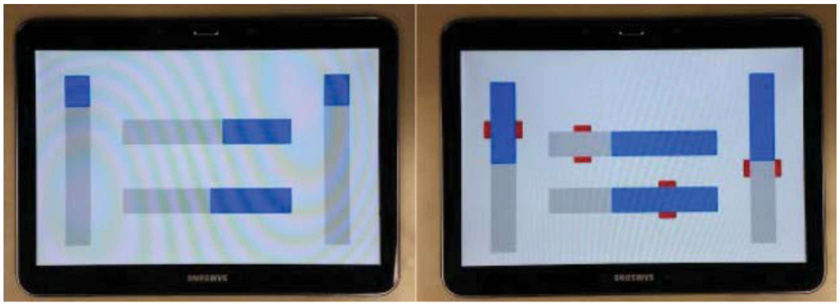


Figure 2.4: Perspex overlay for touchscreen proposed by Colley et al. [15]

Cockburn et al. [13] recently investigated the use of stencil overlays (shown in Figure 2.5) to improve touchscreen interaction while driving. They used 3D printed stencils, contained cuts and holes for touchscreen touch contact, and the rest of the screen was capacitively blocked due to the thickness of the stencil. Because of the transparent stencil, the entire touchscreen was visible. The research was conducted in a dual-task driving simulation setup. The driving task was displayed on a large 50-inch screen, and touch input was captured using a Dell 21.5-inch capacitive touchscreen. The study's findings revealed that target selection was faster with stencil overlays and reduced visual attentional demands. However, there was no significant difference in error or driving performance. Furthermore, subjects prefered stencil overlays over standard touchscreens.

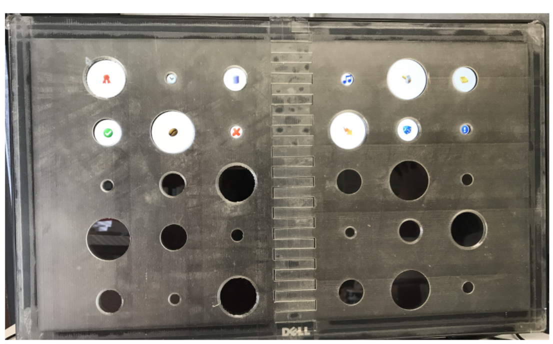


Figure 2.5: Stencil overlay proposed by Cockburn et al. [94]

Voelker et al. [94] proposed tangible rotary knobs for use with touchscreens. The study aimed to compare eyes-free interaction with tangible knobs to traditional touchscreen interaction. In this study, two types of physical knobs were used, as shown in Figure 2.6; (c,e) where the rotor is independent, and (d,f) a tangible pluck where the entire widget was a rotor. Twenty subjects took part in this study and completed a touchscreen rotation task (Microsoft capacitive tabletop display). Subjects evaluated four input techniques: two finger rotation (pinch gesture), single finger rotation (telephone dial), and the two physical knobs mentioned above. The results revealed a significant difference in which touch input was slower than tangible knobs. Because subjects made a significant number of errors, single finger touch was the least precise. However, precision with two fingers (pinch touch) was comparable to physical controls.

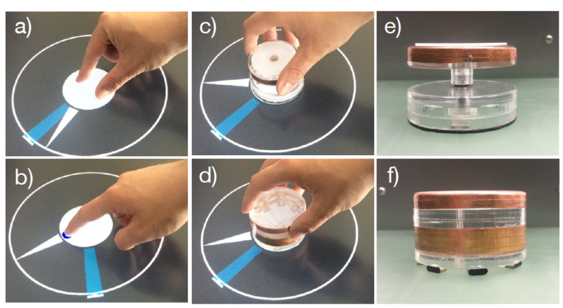


Figure 2.6: Physical knobs for touchscreen [94]

Other research has proposed dynamic augmentations for in-vehicle touchscreens. Miruchna et al. [61] developed the GelTouch overlay for touchscreens, which can provide soft and stiff multi-touch tactile sensations on a touchscreen. Geltouch is a flexible 2mm thin transparent layer that requires heat (>32 °C to change the viscoelasticity of the gel, allowing activated areas to be changed continuously and flexibly. The authors proposed several Geltouch applications, such as buttons, sliders, and thumbsticks. An experiment was conducted out in a dual-task driving simulation setup with Geltouch mounted on a touchscreen. In the experiment, subjects operated several functions while keeping their eyes on the road, using a media player UI. The study's findings were not presented in this paper. Several other studies have been conducted by the authors using Geltouch on various electronic devices such as photocopier machines and wearable displays. Similarly, no results were provided.

Figure 2.7: Geltouch overlay for touchscreens [15]

Russomanno et al. [76] introduced another Pneumatic Actuators (Pneu's) (shown in Figure 2.8) that can enable click and feel feedback on touchscreens, similar to GelTouch. Pneu is a thin layer of see-through actuators mounted on a touchscreen that can detect pressure and position. Pneu's necessitate the use of additional equipment, such as electronic valves to control the pressure. The research was conducted out in a dual-task driving simulation setup. The main task was to drive the car with the help of a steering wheel. The secondary task was to type Numbers on a small touchscreen (keypad interface). The authors compared three different testing conditions, which are as follows: 1. a standard touchscreen keypad interface, 2. a pneu keypad interface (two profiles, bubble and click), and 3. a traditional numerical keypad According to the study findings, the traditional keypad was more accurate than (touchscreen and Pneu) and driving performance was better when using Pneu's click interaction. According to the subjective responses, flat (traditional touchscreen) was rated as the most difficult to use (due to the lack of haptic feedback), while click was rated as the easiest to use.

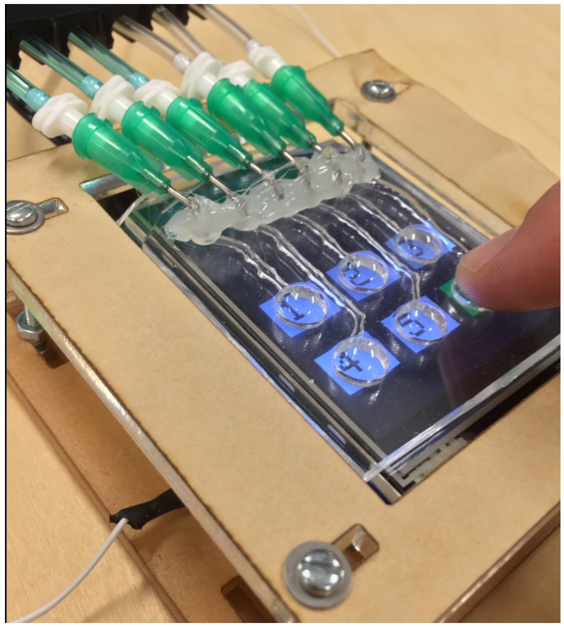


Figure 2.8: Pneu display overlay for touchscreens [76]

2.4.5 Active Tactile Sensations

This section summarises previous research on active tactile sensations for touchscreens. This section is split into two parts. The first section discusses related work on vibrotactile feedback, while the second discusses previous studies on ultrahaptics feedback.

2.4.5.1 Vibrotactile Feedback

For more than a decade, vibrotactile feedback has been widely used in touchscreens (particularly mobile devices). A touchscreen display is vibrated using programmatic control to produce physical sensation when a contact is made with the display in vibrotactile feedback. In general, vibrotactile feedback is produced when a finger is placed on an interactive element of a touchscreen. Several researchers have investigated the use of vibrotactile feedback to reduce attentional demands for in-vehicle touchscreens [4], [38], [67]–[69], [78], [93], previous studies are presented below.

Serafin et al. [69] compared vibrotactile feedback to visual and auditory feedback in a non-driving context in an early study of automotive touchscreens. The authors evaluated uni-modal feedback ('visual only'), bi-modal feedback ('auditory and visual' and 'haptic and visual'), and tri-modal feedback ('auditory, haptic, and visual'). The experiment was conducted in a Ford Focus C-Max. In the centre of the dashboard, a touchscreen was installed. Mechanical actuators were installed on the touchscreen to provide haptic feedback. In the experiment, the media player interface was used, and subjects performed various tasks such as track change, forward/rewind track, play/pause track, and shuffle track. Users prefered bi-modal (visual plus auditory or haptic feedback) over visual alone, with tri-modal feedback being the most prefered. While driving, participants also expressed a preference for tri-modal feedback on a touchscreen.

Several other studies were later conducted that evaluated various combinations of feedback techniques in a driving simulation environment [4], [67], [68], [72], [93]. Richter et al. [67] evaluated 'HapTouch' for an in-vehicle information system (IVIS) that included force-sensitivity and vibrotactile feedback. According to the mean values, vibrotactile feedback improved performance. The study conducted by Beruscha et al. [4] reported no difference in target selection accuracy with different feedback techniques; however, gaze-away time reduced with haptic feedback while driving. Pitts et al. [67], [68] conducted comparable studies and found that subjects prefered the trimodal approach (visual, haptic and auditory). According to a recent study by Tunca et al. [93], haptic feedback reduces errors and visual attention. Previous research has found that haptic feedback can reduce visual attentional demands, reduce error, and is prefered by users over visual and auditory feedback. Interested readers can further read the details of these studies as follows.

Beruscha et al. [4] compared three types of touchscreen feedback: visual, visual+haptic, and haptic only. For haptic actuation, an electrodynamics exciter "*Visaton Ex 45 S*" was used, which was glued beneath an 8.7" capacitive touchscreen and controlled by a Raspberry Pi 2. At each corner of the touchscreen, force sensing resistors were installed. In this experiment, the authors used click and edge feedback signal techniques, which is a continuation of their previous work [25]. The vibration pulse for the edge was set to 150 Hz for 15 ms and two pulses with a 10 ms interval for 15 ms for a click. Experiments were conducted in a dual-task simulation, with the primary task being to drive a car (Lane Change Task) and the secondary task being to select targets on the touchscreen. In all three conditions, subjects had to tap four large targets on the touchscreen (top, bottom, left, and right). The study's findings revealed no significant differences in target accuracy or path deviation across all three conditions. However, gaze-away time was significantly reduced with visual+haptic and haptic as compared to visual feedback.

Pitts et al. [68] evaluated four types of feedback: visual only, visual + audio, visual + haptic, and visual + audio + haptic. Six subjects were withdrawn from the study due to driving simulator motion sickness. Fifty-four subjects were recruited for the study. The study used a 8.4-inch touchscreen. Haptic feedback actuators were preinstalled on the touchscreen. Subjects completed a variety of tasks on the touchscreen that required varying numbers of button presses and levels of menu navigation, such as climate control, audio system, and phone tasks. In the experiment, a lane change task (LCT) was used, in which the subject had to change lanes in response to signs displayed on the side of the road. According to the findings, tri-modal feedback has the highest performance score and was also chosen as the 'most prefered' feedback by the participants. The study did not present any driving or visual attention results.

Pitts et al. [67] investigated the use of visual and haptic for in-vehicle touchscreens. They tested three levels of visual feedback: 'none,' 'immediate,' and 'delayed,' as well as two levels of haptic feedback: 'visual only' and 'visual+haptic.' The experiment was conducted in a Honda Civic cabin equipped with a curved projection screen and projectors that provided full peripheral coverage. To assess driving performance, a vehicle following task was chosen, and subjects were required to follow a vehicle travelling at a constant speed of 68 mph. The driving task consisted of a three-lane highway with the lead vehicle staying in the left lane; the subjects were not required to change lanes during the experiment. The study's findings revealed that the driver was highly reliant on visual feedback, and that when visual feedback was delayed or absent, the driver's glance time increased; a decrease in visual feedback resulted in an increase in visual workload. When haptic feedback was enabled, however, visual feedback levels had no effect on performance. When visual 'immediate' feedback was enabled, haptic feedback had no effect; when visual feedback was 'delayed' or 'none,' haptic feedback improved performance. Furthermore, with haptic feedback, users were able to complete more tasks and saw a reduction in task completion time. When visual feedback was delayed or absent, there was an increase in visual workload, which affected driving performance, increased path deviation, and reduced speed. The study concluded that haptic feedback improved user experience and confidence when interacting with touchscreens.

Tunca et al. [93] conducted a study on touchscreen interaction with and without haptic feedback. The research was conducted in a driving simulation environment. The driving task was to follow a vehicle moving at a constant speed of 70 km/h on a rural road with oncoming traffic on the left lane. The subjects were only required to use a steering wheel to control the horizontal movement of the car. On the right side of the steering wheel, an 8-inch touchscreen was installed. The pressure on the touchscreen was detected using four actuators. The haptic feedback was turned on when the finger pressure reached 3.5 N. The graphical user interface of the touchscreen included four larger buttons (86 mm $\times$ 51 mm in size). The same user interface was displayed in the top left corner of the driving screen as well. The target was marked with a red outline, and subjects were required to select the same target on the touchscreen. A white curtain was placed between the user and the touchscreen to test the glance fee operation. According to the findings of the study, haptic feedback reduces errors significantly and allows for eyes-free interaction with the touchscreen while driving. However, the white curtain used to block the view of the touchscreen had a significant effect on target selection time, and subjects were slow to interact with the touchscreen. In both feedback conditions, there is no significant difference in the driving task. It was also discovered that while driving, the subject prefered not to interact with the touchscreen and instead waited for a straight lane.

2.4.5.2 Ultrahaptics Feedback

Carter et al. [12] introduced another recent feedback technique, ultrahaptics, in 2013. Ultrahaptics use ultrasound projection directly to the display and on the user's hand to provide multi-point haptic feedback above an interaction surface (mid-air). Ultrahaptics has the potential to be used in a variety of applications, including gesture interaction in mid-air. A user relies on visual and audio feedback for confirmation of operation during mid-air gesture interaction. However, with ultrahaptics, a user can receive haptic feedback while interacting in mid-air. Several studies have evaluated ultrahaptics feedback for in-vehicle touchscreens in this regard. The following are some various studies.

Georgiou et al. [28] proposed a demo prototype of ultrahaptics device in early research of ultrahaptics feedback technology (as shown in Figure 2.9). The authors proposed the first interaction technique (hand rotation) for interacting with the touchscreen and receiving mid-air feedback on the user's hand. They proposed that rotating a hand clockwise/anti-clockwise can be used to change the volume of a music player.

Figure 2.9: Ultrahaptics prototype developed by Georgiou et al. [28]

Harrington et al. [33], [53] investigated the use of ultrahaptics for in-vehicle touchscreen interaction. In a driving simulation, the authors compared mid-air gesture control (button selection and slider) to standard touchscreen operation. The study enlisted the help of 48 experienced drivers. The study's findings indicate that combining gesture control with ultrahaptics feedback is promising. During the experiment, a 25% reduction in eyes-gaze direction was achieved, and approximately 40% of subjects were able to complete the task without taking their eyes off the driving screen. The study concluded that using gesture control with haptics was three times more accurate on the slider task than using a touchscreen. On the touchscreen, however, accuracy and selection response were quick in button-selection tasks.

Figure 2.10: Mid-air gestures control with ultrahaptics [33]

A recent study by Young et al. [103] proposed and evaluated several more hand gestures for touchscreens and their respective ultrahaptics feedback patterns. They proposed finger poses menu navigation to switch between touchscreen functions such as media player, air conditioning, and navigation (as shown in Figure 2.11). Each of these touchscreen functions has several controls, and they proposed different gestures to interact with those controls (shown in Figure 2.12). They conducted several studies to evaluate these gestures for in-vehicle touchscreen in a driving scenario, and these gestures were rated as reliable, quick, useful, easy, safe, and realistic. The paper did not include any other results, such as eye-gaze or driving data.

2.4.6 Other Approaches

Prior research has also evaluated into new ways to make in-vehicle touchscreens safer to use while driving. Head-up displays, for example, [57], and secondary head down displays, [7]. Head-up displays refer to displays that are visible to the driver, such as information projected on the vehicle's windscreen. That information can be read by the driver without taking their eyes off the road. Any display that is not directly in front of the driver while driving a vehicle, such as a vehicle

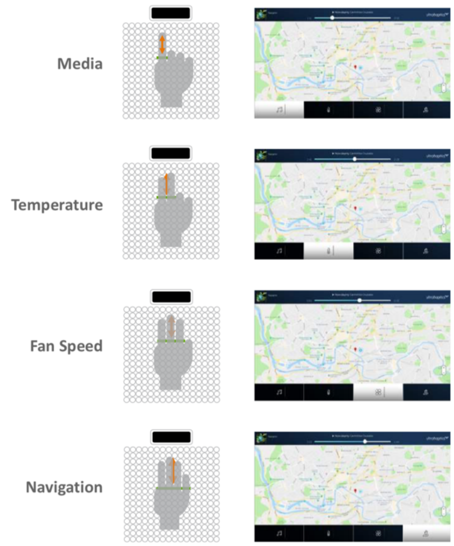


Figure 2.11: Mid-air gestures finger pose menu navigation on touchscreen proposed by Young et al. [103]

infotainment system, is referred to as a head-down display (e.g., touchscreens). In an actual driving scenario, Liu and Wen [57] compared head-up displays to head-down displays. Their study investigated driving performance and reaction time to external events by displaying the same information on both displays. They discovered that head-up displays provided better vehicle speed control, faster reaction time, and lower mental workload than head-down displays. Smith et al. [81] conducted a similar study in which they compared head-up and head-down displays and evaluated other important factors such as gaze-away, path deviation, and speed deviation. They discovered that driving performance on the head-up display was significantly improved, and participants were able to complete the secondary task faster. Head-up displays, on the other hand, necessitated longer glance duration and gaze-away time from the road.

Buchhop et al. [7] proposed a novel method for making touchscreens safe to use while driving. They intend to accomplish this by mounting a secondary display on top of the touchscreen, which will show the live stream of the road while interacting

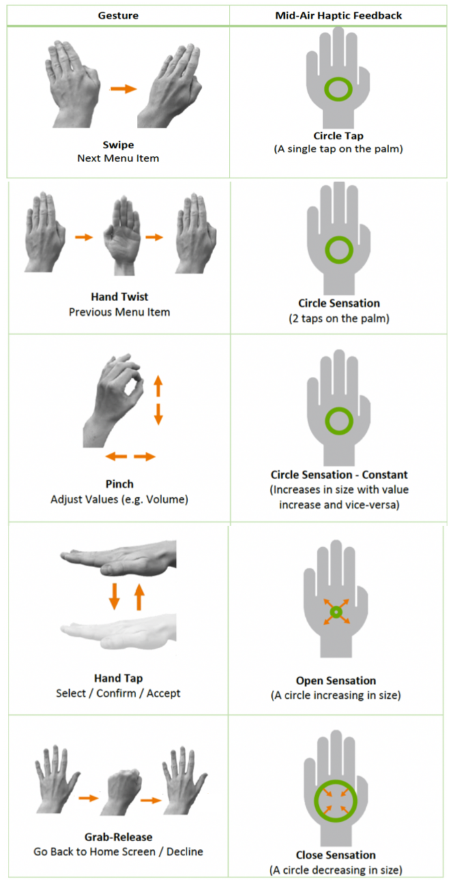


Figure 2.12: Mid-air gestures and ultrahaptics feedback pattern proposed by Young et al. [103]

with the touchscreen. The research was conducted in a standardised lab setup using a driving simulation environment. On a 46-inch display, subjects were shown a video recording of city traffic and pedestrians, as shown in Figure 2.13. Subjects did not perform any driving tasks; the steering wheel was only used to record the driver's perception when confronted with an obstacle. The video recording was altered to include cues indicating how the subject reacts to an obstacle by pressing a lever on the steering wheel. To perform secondary tasks, a 10.5" touchscreen was installed. The secondary task was to select an item from a list (scrolling was required), adjust air conditioning levels, and enter an address in the navigation system using alphanumeric characters. Subjects completed tasks with and without the extra screen. The results show no significant differences in task completion rate, task completion time, or obstacle reaction time.

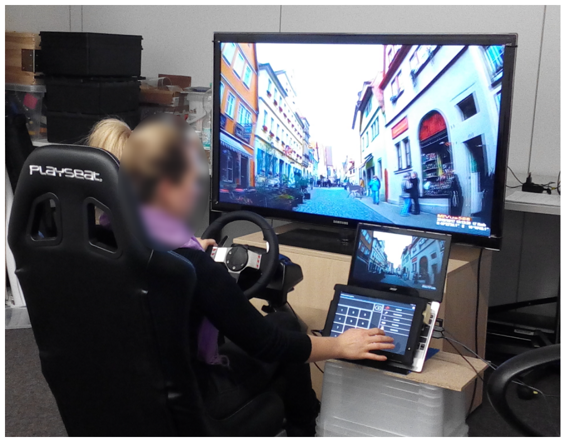


Figure 2.13: Head down display (live strea of road ahead) [7]

2.5 Summary of Prior Work

We reviewed several studies that were conducted to reduce the attentional demands of in-vehicle touchscreens. To summarise the previous contact-based gesture interaction, gesture interaction can reduce the visual attentional demands of a touchscreen. It does not necessitate precise touchscreen interaction, potentially reducing the visual and cognitive demands of in-vehicle touchscreen [3], [8], [36]. However, it was suggested that a limited set of gestures be used, as a large number of gestures could be mentally demanding, leading to cognitive distraction [75]. Furthermore, modern touchscreens provide numerous functions on a single screen, making it difficult to propose gestures for each function on a touchscreen.

Non-contact gesture studies concluded that mid-air interaction improved driving performance. However, gestures were less accurate, caused more errors [60], and were slower [59] than touchscreen interactions. Another study reported 94 percent accuracy with a reliable vision-based system gesture recognition accuracy. Because the majority of these studies lacked eyes-gaze results, it is unclear whether non-contact based gesture interaction can reduce the visual attentional demands of a touchscreen.

Other researchers have evaluated various scrolling techniques to investigate the visual attentional demands of a touchscreen. According to the studies, direct *Swipe* scrolling is faster, more accurate, and less visually demanding than kinetic, on-screen buttons, pressure-based buttons, and physical dial. Kinetic scrolling is the worst of them because it is more visually demanding than the other techniques [50], [54]. Furthermore, any scrolling technique can degrade driving performance, particularly by lowering speed [50], [54]. The decrease in speed indicates that the scrolling input techniques are mentally demanding, resulting in cognitive distraction.

To summarise the studies, we discovered some relevant insights based on touchscreen control sizes, location, and number of controls on the screen. Prior research has shown that large size touchscreen controls require less task completion time, are less visually demanding, and provide better driving performance than small size touchscreen buttons [21], [22], [45]. The size of the touchscreen control has been reported to have a direct effect on other factors such as gaze-away time, number of glances, deviation in driving performance, and change in speed; the larger the size, the safer to use [45]. Kim et al. [45] recommended that any size beyond 17.5mm be underutilised, implying that participants in their study were able to achieve 96% accuracy under 17.5mm on largest such as 22.5m and 27.5mm. Second, the location of controls on a touchscreen has no effect on gaze-away time; however, small controls near the touchscreen's edge have slightly better accuracy [21]. Finally, the number of items (controls) on the touchscreen has a direct impact on other variables such as task completion time, gaze-away time, and the number of glances [26]. These findings were consistent with previous research that found that as the number of distractors increases, visual search efficiency decreases [55], [80], [101].

We discovered that static and dynamic physical augmentations are likely to reduce visual attentional demands and enable eyes-free interaction for in-vehicle touchscreens by reviewing prior physical augmentation studies. Prior approaches to physical augmentation, on the other hand, have some limitations. Prior static physical augmentations proposed by Robert Kincaid [47], Colley et al. [15], and Cockburn et al. [13] were based on cuts and holes, and were limited to a single underlying user interface layout. This constraint is impractical for modern in-vehicle user interfaces, which use different layouts in different parts of the system (such as radio and air-conditioning). In this regard, a new design of physical augmentations/stencils that can provide tactile sensations for touchscreen controls regardless of the underlying user interface can be proposed.

GelTouch [61] and Pneu [76] dynamic physical augmentations also demonstrated the potential to improve touchscreen interactions. The existing studies, however, were mostly inconclusive and lacked important results, such as eye-gaze and driving data. Furthermore, prior dynamic physical augmentations were only tested on small touchscreen sizes and with simple user interfaces (e.g., numeric keypad and media player controls). More tests are needed to evaluate different interaction techniques, functions, and touchscreen sizes.

Previous research on vibrotactile feedback in simulated driving found that it can reduce visual attentional demands, reduce error, and is prefered by the user over visual and auditory feedback. Previous research has found that vibrotactile feedback reduces gaze-away time when compared to visual feedback [4], [93]. According to Pitts et al. [67], if visual feedback is present alongside vibrotactile feedback, users are more likely to rely on visual feedback. Despite these encouraging results, several factors must still be evaluated. Prior research was conducted out in a simulation setup in which the subject was not subjected to any vibration caused by the car engine or road conditions. To obtain more realistic insights into the use of vibrotactile feedback, a study in a real driving environment or on a driving simulation that replicates the vibration of an actual car is required. Furthermore, previous studies on large screens failed to show any significant difference [62], [63].

Ultrahaptics is a new feedback method that is gaining popularity in the automotive industry. Previous ultrahaptics research has shown a significant reduction in gaze-away time and improved driving performance [12], [53]. However, ultrahaptics feedback has several limitations that require further research to make it a more realistic approach in a real-world driving scenario. To begin receiving mid-air feedback, a user must interact with the touchscreen using non-contact mid-air gestures. According to previous research, non-contact gesture interaction is less accurate than touchscreen interaction, which can lead to more errors while operating. Second, prior studies recommend using a limited set of gestures due to cognitive demands required to learn and perform these gestures. This limitation would also be difficult to implement in modern touchscreens, such as Tesla's, because modern touchscreens have so many functions compared to touchscreens from the previous decade. The third untested limitation is how ultrahaptics feedback performs in a real-world driving scenario, as well as how external wind from open car windows or a convertible car affects ultrahaptics feedback. Finally, mid-air gestures can be misinterpreted by the passengers in the car and other people walking on the road.

Chapter 3

Layout-agnostic Stencils for In-vehicle Touchscreens

Previous research indicates that stencil overlays can reduce the visual attention requirements of in-vehicle touchscreens [13], [15], [43], [47], [92]. The previously studied stencils, on the other hand, were *layout-specific*, limiting their use to a single underlying user interface layout. This is an unrealistic constraint for modern vehicle multi-function displays. As a result, we designed a series of *layout-agnostic* touchscreen stencil overlays, with the term "layout agnostic" capturing our intention that the stencils should provide the benefits of tactile guidance for selecting user interface targets regardless of the underlying interface layout — the stencils are agnostic to the interface layout.

The work presented in this chapter aims to investigate the design and use of layout-agnostic stencil overlays for in-vehicle touchscreens. This research involved the development of design goals for layout agnostic stencils, as well as stencil design, development, and evaluation. The following subsection discusses the design goals for layout-agnostic stencils.

3.1 Design Goals

We have set four primary design goals motivating the design of layout-agnostic stencils, presented as follows.

3.1.1 Goal 1: Minimise Demands of Visual Attention

When a driver looks away from the road ahead to interact with the dashboard controls, their visual attention is diverted from the critical task of observing the road ahead, and the driver may miss external events (e.g., another vehicle or a pedestrian), potentially resulting in an accident. As a result, the operations of the in-vehicle touchscreens must be minimally visually demanding. In this regard, we intend to create a new touchscreen interaction system that would reduce visual attention by allowing the user to select items on any underlying interface using proprioceptive knowledge and tactile sensations from the stencil.

3.1.1.1 Proprioception and Tactile Sensation

Once a driver has learned where the controls are, they can use proprioceptive awareness to guide their hand to the general vicinity of the control, reducing the need for visual attention. If the control is large enough (such as a handbrake or gear lever), proprioception alone may be sufficient to acquire and manipulate it. When proprioception is insufficient to acquire the control, tactile sensation may still allow for eyes-free acquisition by feeling for the control's distinctive shape and that of its neighbouring controls (e.g., feeling for a volume control knob to the left of a button panel).

We intend to enable eye-free target acquisition and manipulation by augmenting the touchscreen with a layout-agnostic stencil that provides the user with adequate tactile guidance.

3.1.2 Goal 2: Minimally Invasive on Existing Touchscreen Systems

We aim to develop a new in-vehicle touchscreen interaction system that is minimally invasive on existing touchscreens. The term ‘minimally invasive’ refers to the new system’s compatibility with existing in-vehicle touchscreens. It should, for example, support existing interface layouts, interaction mechanisms, as well as new features and updates, without modifying existing systems.

3.1.2.1 Support Existing User Interfaces and Interaction Mechanism

Introducing a new interaction system that supports existing touchscreens may shorten the learning process due to the driver’s prior knowledge and experience with in-vehicle touchscreens. Our layout-independent stencils are designed to work with the existing interface layout and interaction mechanism without requiring any changes. Our layout-agnostic stencils could be used with any underlying user interface and could potentially support existing touchscreen interaction techniques such as tap, swipe, rotate, and pinch interaction.

3.1.2.2 Allow New Features and Updates

One of the key advantages that touchscreens have over mechanical dashboard controls for manufacturers is design malleability: new functions and interface components can be added to the touchscreen via over-the-air updates without requiring hardware modifications. Through layout-agnostic design, our stencils are intended to work with any underlying user interface, regardless of UI modification.

3.1.3 Goal 3: Minimal Cognitive Demands

When a driver engages in secondary tasks, such as using a touchscreen, talking to someone, or using a mobile phone, cognitive load is another important factor that can cause a distraction while driving. Prior research has shown that when a driver is cognitively distracted, they tend to increase/decrease headway distance to the lead vehicle (due to quick braking and acceleration), increasing the risk of an accident [51], [88].

Paying high attention to secondary tasks in a vehicle could influence driving performance. For example, suppose the driver is attempting to search for a location on a maps application on a touchscreen and has no prior experience with maps applications. A sophisticated application's user interface or drivers' lack of experience with touchscreens may increase cognitive demands, affecting driving performance. The cognitive demands of using an in-vehicle touchscreen should be kept to a minimum. By simplifying the interaction mechanism, the cognitive demands of in-vehicle touchscreens can be reduced.

3.1.3.1 Simple and Easy to Learn Interaction Mechanism

In-vehicle touchscreens offer design flexibility to handle multi-input/output functions on a single screen by changing the display state. A media player, for example, can be displayed on one display state while radio controls or maps are displayed on another. Because of the learning process to use all functions, switching between functions, and different functions use different interaction mechanisms, this touchscreen property may increase cognitive demands. A tap interaction, for example, is used to change the music track on the media player, and a tap and hold interaction is used to forward/rewind the track. Having multiple functions and interaction mechanisms on a single display may place additional cognitive demands on the user.

As a result, we intended to keep our layout-agnostic stencils interaction mechanism simple and simple to learn. We intended to use an interaction mechanism that the users are already familiar with, and if not, we planned to teach them a new interaction mechanism that would be minimally cognitive demanding.

3.1.4 Goal 4: Low Task Completion Time

Another factor to consider when designing a new system is task completion time. The time it takes to complete a task can have an impact on the cognitive and visual demands of using a touchscreen. Longer task completion times increase the possibility of distraction.

Our layout agnostic stencils are likely to increase target acquisition time beyond that required for a visually guided selection. To facilitate eyes-free interaction, we prioritise reducing visual attentional demands over task completion time. We do not mind if the task takes longer than a standard touchscreen as long as it is less visually demanding. Our first and most important design goal is to reduce the need for visual attention because visual distraction has a higher risk of an accident than cognitive distraction [48]. However, we intended to minimise the task completion time as low as possible.

3.2 Layout Agnostic Stencils Design and Development

This section describes the design and development of layout-agnostic stencils for in-vehicle touchscreens. Before going any further, it is important to define two terms (proprioception and tactile sensations), which are used frequently throughout this chapter and the rest of the thesis. Proprioception is the ability to perceive the location, movement, and action of body parts. Tactile sensation is the sense of touch, specifically the information received from varying pressure or vibration against the skin.

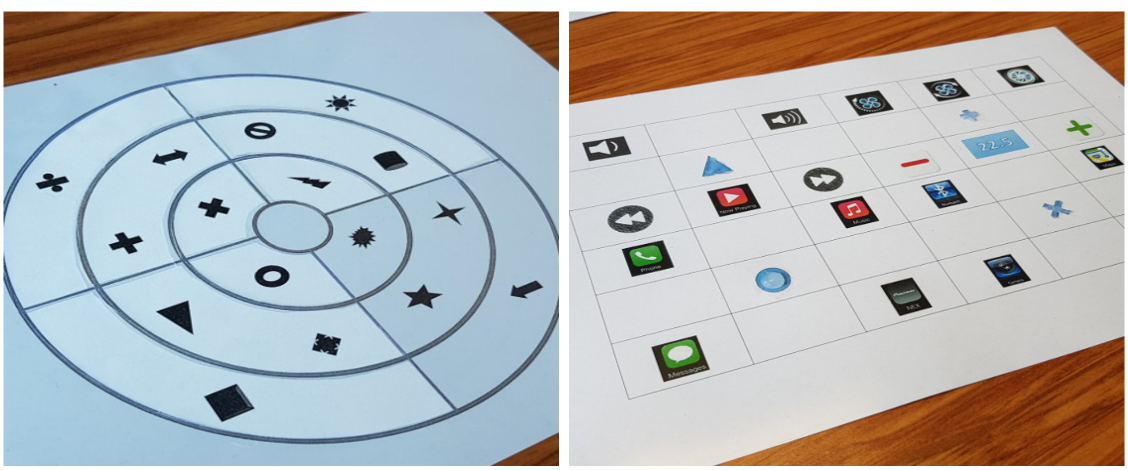
Several previous studies suggest that stencil overlays can provide tactile sensations to underlying touchscreen controls and have the potential to reduce attentional demands [15], [47], [61], [76]. A recent study by Cockburn et al. [13] also confirmed that layout-specific stencil overlays could reduce attentional demands while driving. In this regard, we aim to design and test a number of layout-agnostic stencils.

The tiny nubbins on the 'F and J' keys on a standard keyboard inspired the idea of layout-agnostic stencils. These tiny nubbins were designed to help users place their index fingers on these keys without having to look at the keyboard. The tactile sensation of these nubbins alerts users that they have placed their fingers on the correct keys, and they begin typing. Without these nubbins, a typist would have to position their fingers by looking at the keyboard. These tiny nubbins reduce the need for visual attention. A similar approach called Braille touch is also used for blind people to read and write. Blind people can read by using tactile sensations provided by raised dots. Each raised dot pattern represented a syllable or a word. Braille is commonly used in public places such as elevators and ATMs. The potential of tiny nubbins on keyboard keys and Braille touch. To reduce the need for visual attention, a similar design can be applied to in-vehicle touchscreens with the help of a stencil.

The general interaction mechanism on layout-agnostic stencils is that users are expected to reach the initial features of the stencil (e.g., nubbins or ridges) solely through proprioception. The user then guides their finger to the underlying touchscreen control using tactile sensations from features on the stencil (e.g., sensations on the nubbin or ridges) without looking or with a brief glance. The use of proprioception and tactile sensations can allow the user to interact with a stencil mounted on top of the touchscreen to reduce visual attention.

3.2.1 Initial Prototypes: Web and Nubbin

The layout-agnostic stencil design process began with two concept designs, as shown in Figure 3.1. The first design was a web-based stencil as shown in Figure 3.1a; a web pattern was carved with an office knife on a transparent latex sheet. The second design was based on nubbins; four different shapes (e.g., Triangle, Square, Plus, and X) were attached to the transparent latex sheet as shown in Figure 3.1b.



(a) Grid stencil (b) Nubbin stencil

Figure 3.1: Initial layout-agnostic stencil concept designs.

3.2.1.1 Design

The web-based stencil's interaction mechanism was as follows: The initial feature/starting point of interaction could be the web's centre (a circle). The users are only supposed to use proprioception to get to the centre of the stencil. Once in the centre, the user can drag a finger over the desired target and release it to complete the acquisition. The user could get tactile sensations from the ridges (e.g., black lines as shown in Figure 3.1a of the web pattern) while moving the finger towards the target from the centre. The direction of finger movement and tactile sensations from the ridges could help the user remember where the underlying touchscreen controls are. For example, the 'division' icon is located 40° or NW direction of the centre after three ridges. The user may be able to memorise the location of controls and tactile sensations from the ridges, reducing the need for visual attention.

Similarly, in a nubbin-based design, the four nubbins (e.g., Triangle, Square, Plus, and X as shown in 3.1b can be the initial features/starting point of interaction. The users are only supposed to use proprioception to reach nubbin. Once the users have located the nubbin's approximate location, they can move their finger across the stencil to experience tactile sensations from the nubbins. Nubbins' distinct tactile sensations can help users memorise, identify, and acquire nearby underlying touchscreen controls. The call receive button, for example, was on the North-West position circle nubbin. The user could interact with the touchscreen controls without needing visual feedback by using tactile sensations and associating touchscreen controls with nubbins.

3.2.1.2 Method

We enlisted the help of five postgraduate students from a local university to provide feedback on these concept designs. All of these users rely on touchscreens in their vehicles on a regular basis. Subjects were briefed on the purpose of these concept designs as well as how they will function on in-vehicle touchscreens. Each subject spent 1–2 minutes on these designs to explore the potential use-cases and to freely interact with them. Subjects were then asked to provide feedback on these concept designs, specifically how they could be implemented as an overlay on top of in-vehicle touchscreens to provide tactile sensations and enable eyes-free interaction while driving.

3.2.1.3 Findings

Each of these designs is unique, according to the subjects, and can be used in a variety of ways. They suggested that for the Grid design, the centre of the stencil might be difficult to reach at first, but that it is possible with appropriate training, just as we can reach other controls on the dashboard, such as knobs and buttons, without looking at all. One participant also stated that if the centre point of the grid-based stencil has some texture, it will be easier to locate because it will have different tactile sensations than the rest of the touchscreen surface. Subjects also stated that the grid-based design could be used completely eyes-free; however, a quick glance to the centre may be required, and the rest of the interaction would be less visually demanding.

For nubbin design, subjects reported that these nubbins have a different feel due to their distinct shape and can be easily identifiable with touch. However, one subject reported that *'it was hard to differentiate between "Plus and X shape" due to their identical shape'*. The subjects also reported that locating nubbins was easier than grid design because these nubbins are larger and have more tactile sensations than the centre of the web stencil and ridges. *'these nubbins are similar to PlayStation controller shapes, so it makes them easy for me to memorize their location on the stencil'*, said one subject.

In general, we received positive feedback on both designs, as well as some suggestions. Subjects were enthusiastic about mounting these designs on in-vehicle touchscreens and expressed confidence in the ability of both designs to use touchscreens without looking. Subjects were also eager to test the final 3D printed stencils and take part in the experiment.

3.2.2 Final Stencil Designs

Based on prior study recommendations and findings of initial concept stencil designs, as well as positive feedback from actual in-vehicle touchscreen users. We decided to continue our investigation into layout-agnostic stencils. To design and select the best layout-agnostic stencils, we created and tested various prototypes until we found the ideal designs for our research. We finalised four stencil designs based on prototypes and testing, which are as follows: Web stencil, Corner Curve stencil, Grid stencil, and Nubbin stencil. Each of these designs is presented separately in the subsections that follow.

In terms of Study-I design goals, all of our stencils ports Goals 1 through 3 are explained below. The tactile sensations on the stencils may reduce the need for visual attention, so *'Goal 1: Minimize demands of visual attention'*. because we are not modifying the underlying touchscreen controls, we are mounting an overlay on top of the touchscreen. because we use a simple interface layout and interaction metaphor with which users are already familiar due to their use of touchscreen smartphones and other touchscreen devices. Grid-based stencils partially port *'Goal 4: Low task completion time'* because we anticipated that the task completion time would be longer than on a standard touchscreen.

During the stencil design process, we considered several factors such as layout, material, visibility, friction, texture, and material thickness for touch capacitive stencils. Because of its transparent optical visibility and touch-capacitive properties, we chose *Vero Clear*. To design these stencils, we used Solidworks CAD software. All of the stencils were printed on a 'Connex 350' printer. In addition, none of the 3D-printed stencils were optically clear. As a result, we cleaned these stencils with multiple 'Sanding sheets wet and dry' and then sprayed them with 'Clear Coat' spray to improve visibility.

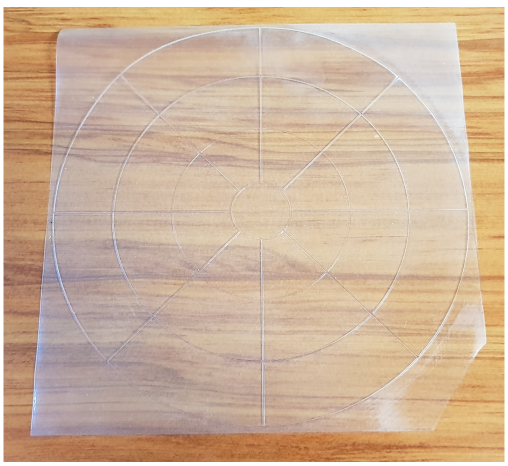
3.2.2.1 Web Stencil

We printed the first stencil, called Web stencil, based on our initial concept design. The web-based stencil is built on web patterns, which are ridges that provide tactile feedback to the underlying touchscreen controls. The interaction mechanism is the same as described in the initial concept design.

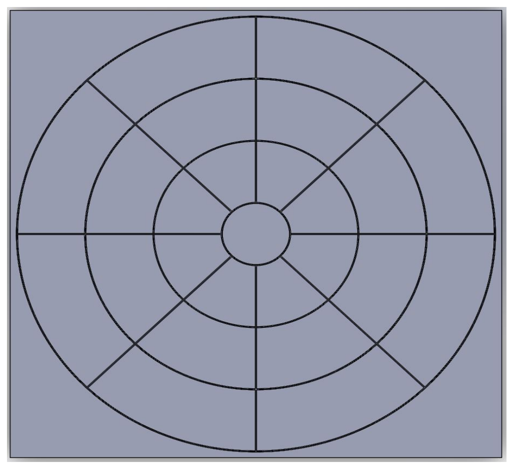
We tested several prototypes before printing the final Web stencil design to evaluate interaction issues. Figure 3.2 shows the first prototype, which was printed with the following properties: 0.5mm and 1mm ridge height, 25mm centre radius, and 25mm distance between each ridge. We evaluated the first prototype and discovered several design flaws. First, the 1 mm ridge height was too high, making it difficult to drag the finger across the stencil and causing the finger to lose touch contact while dragging. Second, the 25mm centre radius of the web was too large to locate using only proprioception; we could not tell if our finger was in the centre or elsewhere on the stencil.

Figure 3.2: Web stencil prototype version 1.

We took into account all of the flaws discovered in our first prototype and made the necessary changes. The second prototype (shown in Figure 3.3) was printed with the following properties: Height of the ridges was 0.5mm, the centre radius was 12.5mm, and diagonal ridges had been added to provide more tactile sensations when dragging diagonally. The second prototype addressed the issues that had been identified in the previous design. However, we discovered that it was still difficult to locate the centre of the web stencil at first, though this can be accomplished with some proprioceptive training. We also added texture to the centre to provide a more tactile sensation in order to make the centre stand out.



(a) 3D Printed



(b) 3D Model

Figure 3.3: Web stencil prototype version 2.

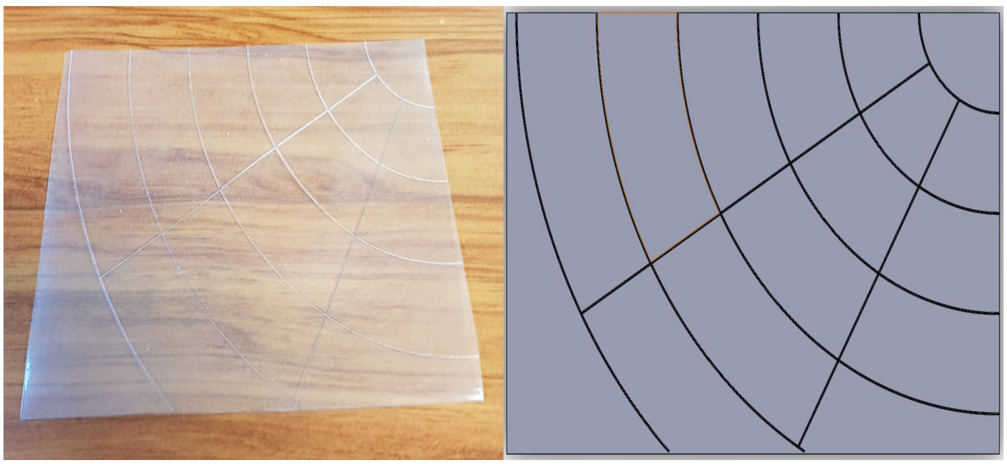
We printed our final design of '*Web Stencil*', as shown in Figure 3.4, based on the evaluation of prototypes. This stencil was printed with the following properties: 292 × 201 mm (including bezels), 0.25 mm thickness, 0.5 mm ridge height, and 12.5 mm centre radius The 0.5mm ridge height provided rich tactile sensations, and the 12.5mm centre radius was large enough to be reached using proprioception. We matched the size of the stencil to the size of the touchscreen we used in the experiment, and we kept the same size for all other stencils.

Figure 3.4: Final version of Web Stencil.

3.2.2.2 Corner Curve Stencil

It was identified and supported in prior studies that people grasp the corner of a display device to stabilize their hand, making it easier to interact with the display [16]. Locating the corner of the display is also easier than reaching the centre of a display due to its distinctive physical properties. We could grasp the corner of a display without looking at all using proprioceptive knowledge. It is similar to reaching and grasping physical dashboard controls using proprioception and tactile sensations. Once the user grabs the corner of the display, they can guide their hand to reach a certain location and complete target acquisition.

Keeping in mind the concept of grasping, we have developed a new stencil named '*Corner Curves Stencil*'. The intended interaction mechanism on corner curve stencil was as follows. The user first grasp the corner of display using proprioception then place a finger inside a corner on a display, drag the finger over the target and release it to complete the acquisition. While the users drag the finger from corner to the target, they could get tactile sensations from the ridges, similar to the Web stencil. The users can memorise the location of targets on the touchscreen with ridges pattern. For example, target 'X' was at 45° from left bottom corner after two ridges.



(a) 3D Printed (b) 3D Model

Figure 3.5: Corner curves stencil prototype version 1.

We printed the first Corner curve stencil prototype with the following properties (as shown in Figure 3.5): 0.5mm ridge height, 25mm distance between ridges, and diagonal ridges at 30 degrees of the corner. We discovered that locating the corner of the display and guiding the finger to the other part of the display was possible by evaluating this design. The ridges on the stencil provided rich tactile sensations that assisted in guiding the finger across the stencil without visual attention.

Figure 3.6 shows the final version of *Corner Curves Stencil*. The stencil was printed with the following properties: 292×201 mm (including bezels), 0.25mm thickness, 0.5mm ridge height, 25mm distance between ridges and diagonal ridges at 30 degrees of corner.

Figure 3.6: Final version of Corner Curve Stencil.

3.2.2.3 Grid Stencil

The corner grasping approach we used to design the *Corner curve stencil* resulted in a new stencil design. While testing the Corner Curve stencil, we discovered that it was also possible to reach and grasp the display's bezel (sides). However, the display's bezel may vary in size (depending on the size of the display), and it may be difficult to tell which exact location of the bezel we are currently in contact with without looking. This issue can be resolved by adding tactile sensations to the bezel. Tactile sensations on the bezel can guide the user to the precise location of the hand on the bezel. Once the user knows the exact location of their hand, they can interact with the touchscreen without having to look at it. We created a stencil called *'Grid Stencil'* based on this concept.

We decided to add physical landmarks in the form of ditches and bumps to provide tactile sensations on bezels. We have put 16 landmarks on the display bezel, four on each side. The following were the profiles of landmarks: Circle ditch and Square ditch with a depth of 2mm and a diameter of 12mm, Circle bump and Square bump with a height of 0.5mm and a diameter of 12mm Ridges were used to connect identical landmarks on opposite sides of the bezel. By connecting the cuts and holes with these ridges, a grid of (5×5) 20 blocks was formed. By placing these landmarks on each side of the bezel, users can begin interacting with the display from any angle or position. paragaph

Figure 3.7: Final version of Grid Stencil.

The Grid stencil's interaction mechanism was as follows. The user uses proprioception to reach the display bezel (close to the target on the touchscreen), then drags the finger over the target and releases it to complete target acquisition. These ridges can help the user guide their finger across the touchscreen.

Figure 3.7 shows the final version of Grid Stencil. The following properties were printed on this stencil: 292×201 mm (including bezels), 0.25mm thickness, 0.5mm ridge height, and four landmarks on each side of the stencil bezel (circle ditch and square ditch at a depth of 2mm and diameter of 12mm, circle and square at the height of 0.5 mm and diameter of 12mm).

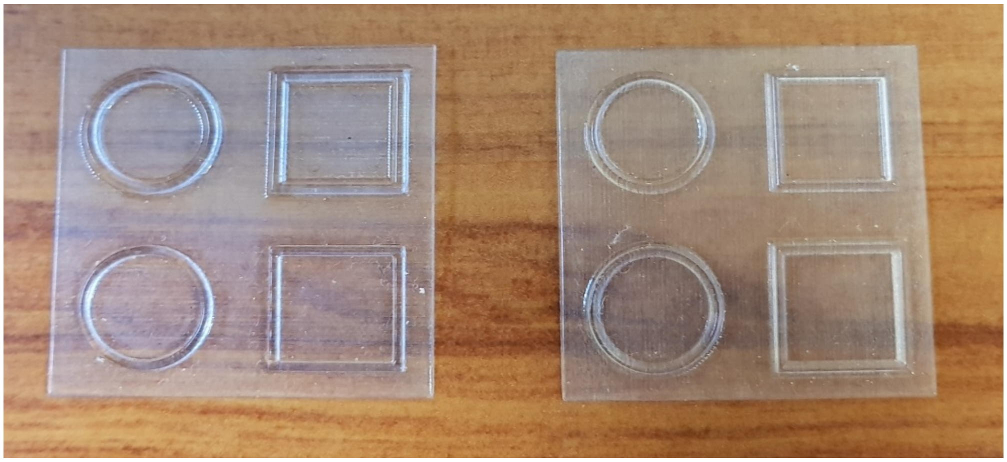
3.2.2.4 Nubbin Stencil

The second initial concept design was based on Nubbins. As a result, we decided to design a stencil based on that concept. The interaction mechanism on the Nubbin stencil was identical to the one we tested in our initial concept design.

We discovered two major flaws in our nubbin stencil concept design. First, the nubbins were unrecognisable due to their similar properties, such as the '+' and 'x' shape. Second, increasing the height of the nubbins may result in a loss of touch contact with the display. Given these concerns, we decide to print and test some nubbin prototypes before printing the final design. We used ditch profiles similar to those used in the *Grid stencil* in these designs because it was easy to drag the finger from the ditch without losing touch contact.

Figures 3.8 and 3.9 show prototypes. We printed these prototypes with the following properties: Figure 3.8a, 0.5mm and 1mm ridge width, ridge height at 0.5mm and 1mm and 12mm radius.

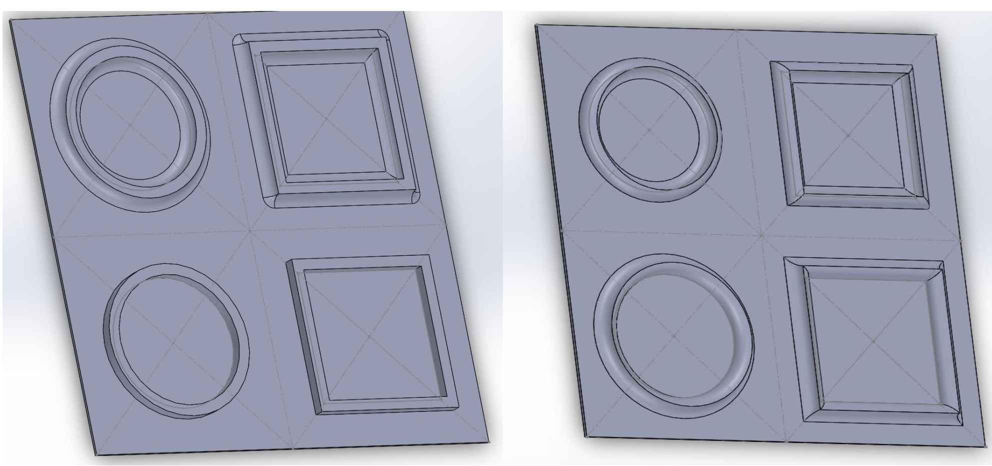
We discovered that 1mm ridge width was too broad, causing lift-off errors on the touchscreen, and 1mm ridge height was too high, causing two problems: losing touch contact and obstruction with large fingernails. We printed another prototype, as showsn in Figure 3.8b, with the following properties: 0.25mm and 0.5mm ridge width, 10mm and 12mm radius, and 0.5mm ridge height. We discovered that



(a) Nubbin prototype version 1 (b) Nubbin prototype version 2

Figure 3.8: Nubbin prototypes.

12mm radius was still too large for the index finger after testing these prototypes; thus, 10mm radius was a good size for the general sample.



(a) (b)

Figure 3.9: Nubbin prototypes 3D model.

We printed the final version of the Nubbin stencil (Figure 3.10) with the following properties: 292 × 201 mm including bezels, 0.25mm thickness, two circle and square nubbin with 0.5mm ridges height, 0.5mm width, and 10mm radius, taking into account all of the experiences we gained by evaluating these prototypes.

Figure 3.10: Final version of Nubbin Stencil.

3.2.2.5 Normal Stencil

We also printed a plain stencil called ‘Normal stencil,’ as shown in Figure 3.11, to keep the visibility, touch capacitive, and friction factors consistent with other stencil designs. The normal stencil’s interaction metaphor was ’tap,’ just like the normal touchscreen.

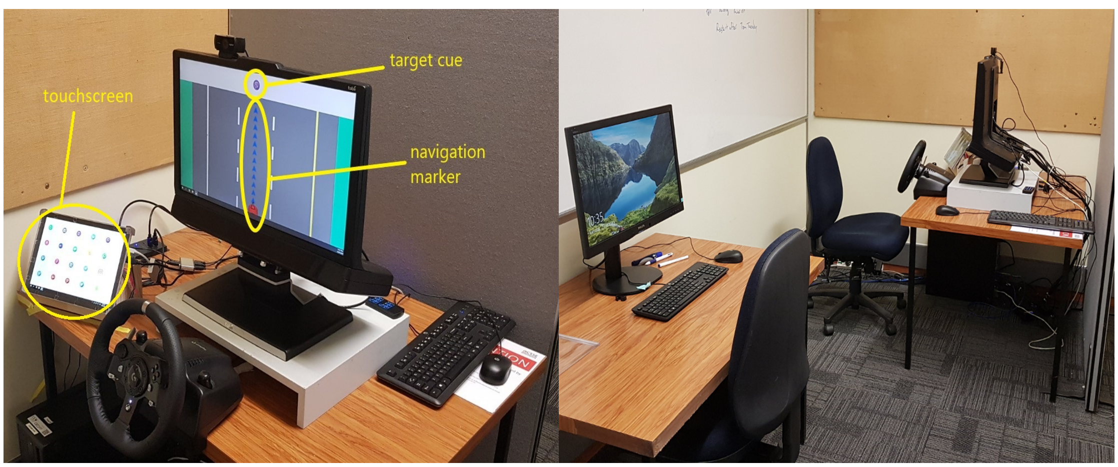
Figure 3.11: Final version of Normal Stencil.

3.3 Stencil Evaluation

This section describes the development of a driving simulator and touchscreen user interfaces, as well as pilot studies on user interfaces, experiment design, experiment procedure, and data analysis. The Human Ethics Committee at the University of Canterbury approved this experiment (approval letter is attached in Appendix B). The subject's information sheet and consent form is also attached in (Appendix C).

The goal of Study-I of this research was to develop and evaluate new touchscreen interaction methods based on layout-agnostic stencil overlays in order to reduce attentional demands in-vehicle touchscreens while driving. The first study involved a series of experiments to design and evaluate the effectiveness of layout-agnostic stencils in comparison with the normal touchscreen. We considered several dependent measures in these experiments, including gaze-away time from the primary task (driving), driving performance, and target selection time and accuracy while driving.

In the experiment, subjects completed a simulated driving task (steering a car) with the steering wheel and selected a cue of targets on the touchscreen mounted on the left side of the steering wheel, as shown in Figure 3.12a. Various measures, such as path deviation and eye-gaze direction, were used to assess driving performance. The touchscreen's performance was measured in terms of target selection time and accuracy in terms of errors (wrong item selection, unintentional touch and lift-off errors).



(a) Subjects seating position (b) Experimenter seating position

Figure 3.12: Experiment setup used in Study-I, showing subjects and experimenter seating position.

The main hypothesis of Study-I **H1: The attentional demands required by in-vehicle touchscreens while driving can be reduced with layout-agnostic stencils**. The H1 is further subdivided as follows for each measure considered. Once the user is expert of using touchscreen with layout-agnostic stencil overlays, it would:

- H_{vd} - reduce visual attentional demands
- H_{pd} - reduce path deviation
- H_{re} - reduce errors
- H_{ts} - reduce target selection time

3.3.1 Driving Simulator

Studies focusing on in-vehicle touchscreens while driving necessitate the collection of driving data from participants in order to analyse their driving performance. This data can be obtained through actual or simulated driving. Most researchers employ simulated driving as a method. The simulated driving is a method that quantitatively measures the human performance degradation on the primary task while a secondary task is being performed. We also chose simulated driving over actual driving to obtain an exact measure of deviation from ideal steering controls, which could be easily accomplished in simulated driving. Furthermore, several prior studies conducted experiments in real-world driving situations, but they did not report any driving accuracy results [3], [63], [64].

Driving simulators are available on the internet in both free and paid versions. The most commonly used simulators are based on the Lane Change Task (LCT) and the Object Follow Task (OFT). LCT and OFT are standardised lab-based methods for quantifying the secondary task's impact on driving performance (e.g., touchscreen interaction). Prior studies based on these driving simulators, on the other hand, failed to produce any meaningful driving performance results. Several prior studies, for example, have failed to show/present any significant results on the Lane Change Task [4], [61], [72] and Object Follow Task [8], [23], [67], [93] when comparing different interaction techniques of secondary tasks while driving.

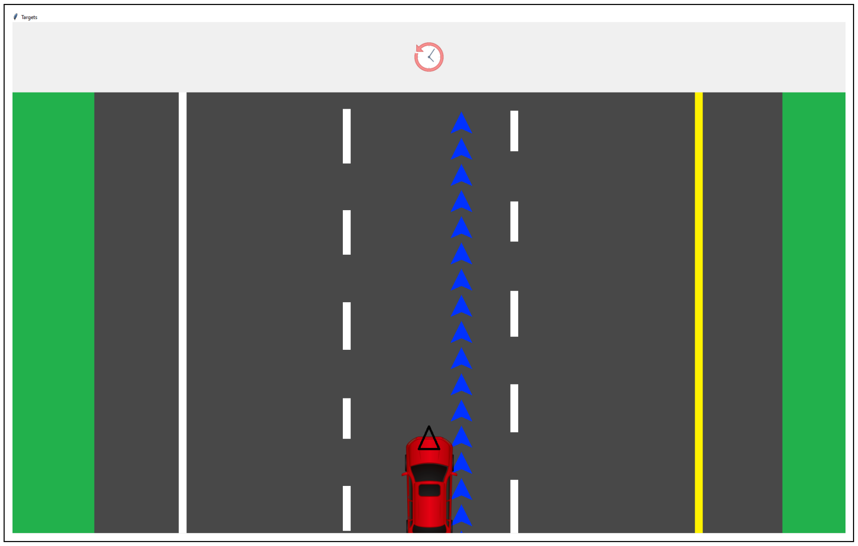


Figure 3.13: Driving simulator showing the car, navigation marker and a target icon.

Given the lack of significant driving performance results from previous studies using LCT and OFT. Cockburn et al. [13] proposed a new approach called *Spline task* to evaluate driving performance. In the Spline task, subjects used the steering wheel to control the tip of the blue arrow as close to the moving sine wave line as possible. Their study's findings also failed to show a significant effect of driving.

For this study, we decided to develop our own driving simulator, as shown in Figure 3.13. The subject only needs to control the horizontal movement of the car using the steering wheel in this simulator. Other car controls, such as acceleration, gears, and brakes, were not used. We hoped that the precise and straightforward driving task would produce more sensitive driving results because previous studies failed to show any significant difference in driving performance when comparing different secondary tasks. The driving setup we used in our studies was far from realistic. It does, however, serve the purpose of the experiment and would produce the expected results. Our main goal was to precisely measure the deviation from ideal steering controls, which we were able to do with the help of this simulator.

Furthermore, the setup was adequate for conducting dual-task experimental studies. The subjects were fully engaged in the driving task (even more challenging than a real-life situation).

The driving simulator proposed here is a hybrid of LCT and Spline tasks. Instead of abruptly displaying lane change signs as in LCT, we have shown a linear navigation marker (blue marker shown in Figure 3.13). As programmed, the navigation marker moves across all three lanes. Using the steering wheel, the subject must keep the car (tip of the triangle) as close to the navigation marker as possible. The car was travelling at a constant speed of 60 kilometres per hour. We determined the car's speed by determining the number of image frames displayed on the driving simulator in one second. The car and navigation marker were initially positioned in the centre lane; however, the marker randomly moves across all three lanes every 5 seconds. It can, for example, move from the right to the centre or left lane, from the centre to the left or right lane, and from the left to the centre or right lane. The Driving simulator was developed in Python language by using PyGame and Tkinter library.

3.3.2 Pilot Studies on Interaction Metaphor for Stencil Overlays

Before running the final experiment, we conducted several pilot studies on the touchscreen's graphical user interface for stencil overlays. We used the following stencil designs in these pilot studies: Web Stencil, Corner Curves Stencil, Grid Stencil, Nubbins Stencil, and Normal Stencil.

Pilot Study-1: We used all five stencils in the first pilot study. The GUI layout for each stencil display was the same: twenty icons were displayed in a grid format.

On stencils, the target selection metaphor was as follows. *drag and release* (half tap) selection metaphor was used. To complete the acquisition, the subjects had to place their finger on a marker (a red circle), as shown in Figure 3.14, then drag the marker over the target icon and release the finger. Concerning stencil designs, each stencil design had a different layout and number of markers, as explained below:

Four markers were shown on the corner curve stencil (Figure 3.14), one in each corner of the stencil. The subject could begin interacting with the touchscreen by dragging any marker (preferably the one closest to the target) over the target icon. On the grid stencil (Figure 3.15), sixteen markers were displayed, each one associated with a nubbin on the stencil's bezel. Four markers were displayed on the nubbin stencil (Figure 3.16), one under each nubbin. Finally, only one marker was displayed at the stencil centre on web Stencil (Figure 3.17).

In these interfaces, we have also included acoustic feedback.'On successful target selection, a 'Pling' sound was played, and on any error, a 'Buzz' sound was played (wrong target and lift-off). In addition, when a target appeared on the driving screen, a 'Beep' sound was played to alert the subject in case they missed visually.

The pilot study followed the following procedure. The practise phase consisted of five blocks. On the touchscreen, five icons were displayed, and the subjects had to select all of them. The training phase consisted of 10 blocks. During this phase, the system displayed twenty icons on the touchscreen and chose five at random as the target items. Lastly, the testing phase consisted of 7 blocks. The same twenty icons from the training phase were displayed; however, the icons were not visible on the touchscreen. The subject was required to select the same five target items without looking at the touchscreen at all. The subject began driving the car, and the first target appeared at the top of the driving screen after 7.5 seconds, followed by subsequent targets every 5 seconds. Every 9 seconds, the navigation marker we used in the driving simulator moved to the another lane at random.

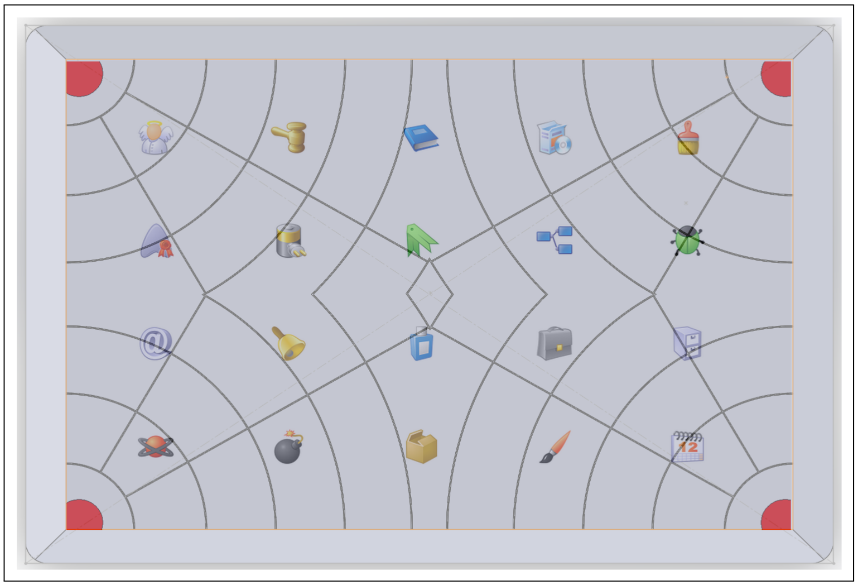


Figure 3.14: Corner Curve stencil GUI version 1.

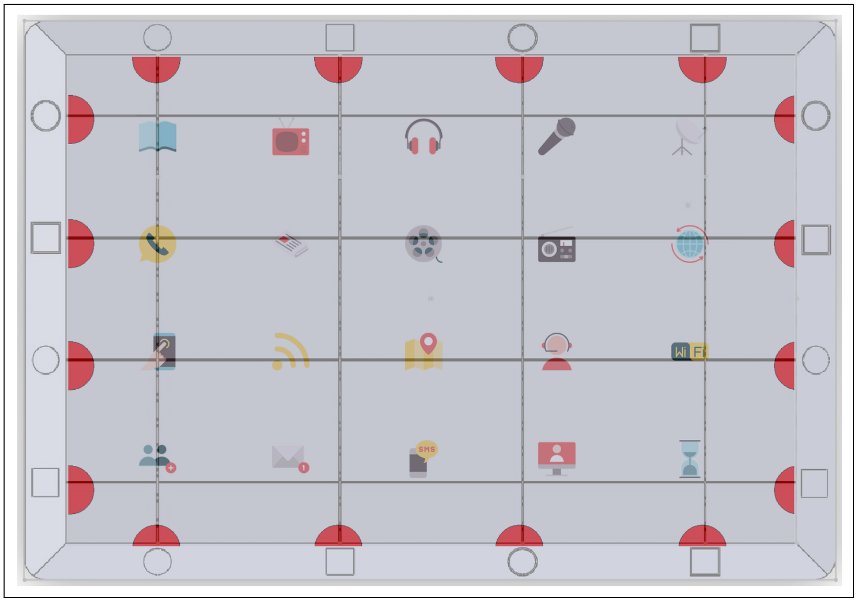


Figure 3.15: Grid stencil GUI version 1.

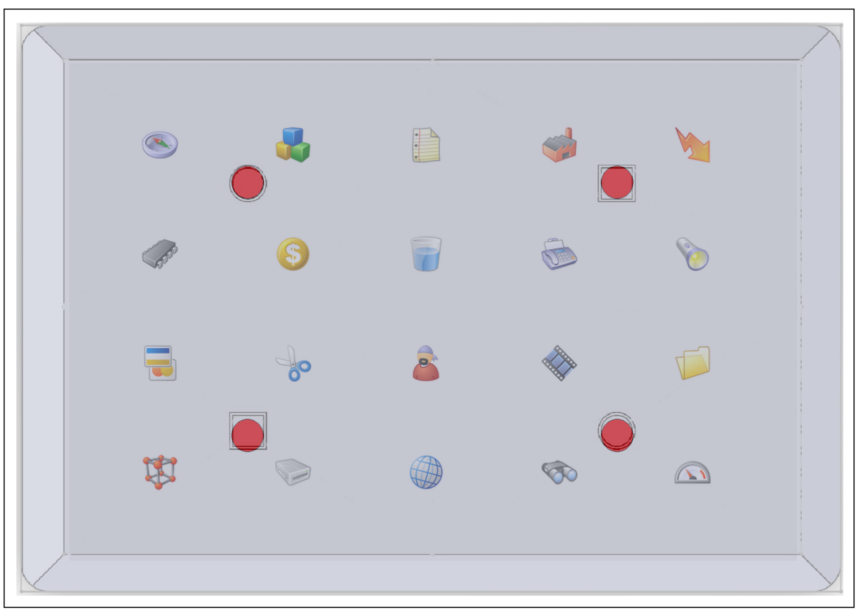


Figure 3.16: Nubbin stencil GUI version 1.

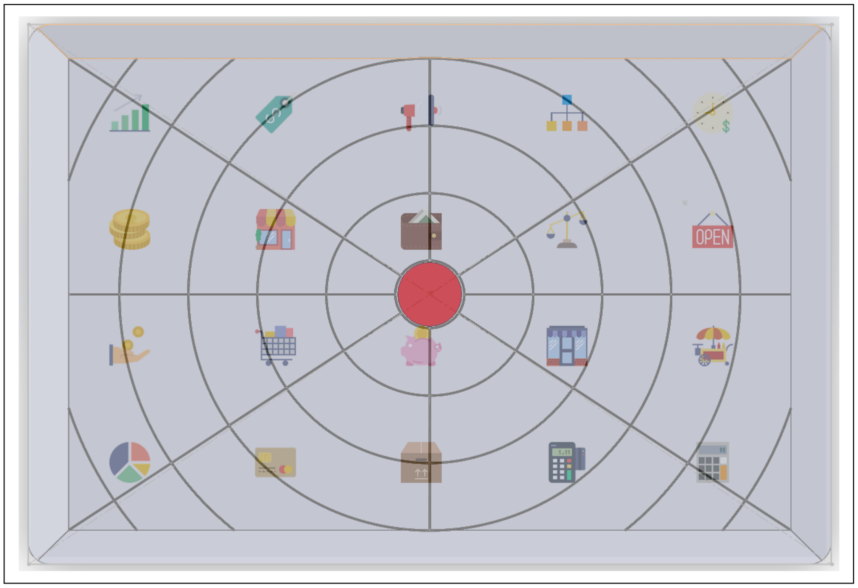


Figure 3.17: Web stencil GUI version 1.

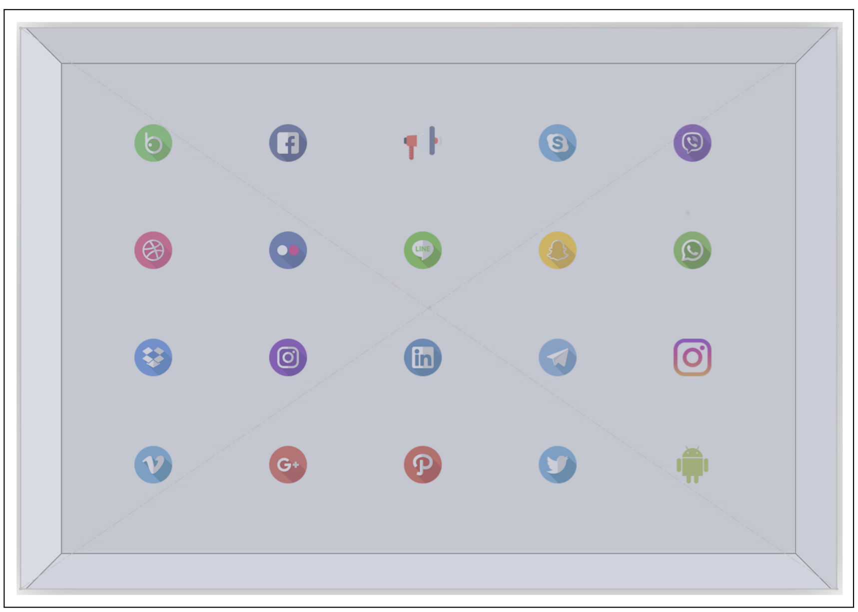


Figure 3.18: Normal stencil GUI version 1.

Results of Pilot Study-I: We discovered several flaws in the experiment design during this pilot study. First, selecting the target icons on the touchscreen without looking was difficult, increasing visual attentional demands. Subjects were unsure whether they had correctly placed their finger (via proprioception) on the marker. Second, the time interval between target appearances was too long, and subjects spent too much time driving alone, making the experiment too simple. We intended to experiment with frequent touchscreen interaction while driving. Finally, the lane change time of the navigation marker on driving simulation was quite long, and subjects drove the car on the same path for an excessive amount of time; thus, the driving task was not challenging. We wanted to make the driving task difficult so that we could test our stencils for difficult driving scenarios. For instance, the subjects may be required to use the touchscreen while driving on a hilly road with sharp curves and turns. If users could use these stencils in a difficult driving scenario, they should be able to use them easily in a normal driving situation (e.g., driving on a motorway). All of these concerns have been addressed, and changes have been made as a result.

Pilot Study-2: We used the same stencils and experiment procedure as in Pilot Study-1 in the second pilot study. We did, however, make the following changes. First, we added acoustic feedback on marker drag; when a subject dragged the marker, a continuous sound of 'item dragging' was played. On the touchscreen, only red circles could be dragged; drag was disabled for all other touchscreen icons. This acoustic feedback raises awareness that the interaction process has begun successfully, reducing cognitive demand and the number of errors. When a marker was placed over any icon on the touchscreen, we added a beep sound. This beep sound could help subjects release their finger from the touchscreen because they would knew the marker was on an icon. Third, in all display conditions, we reduced the appearance time of the first target to 5 seconds and subsequent targets to 2.5 seconds, requiring subjects to interact with the touchscreen more frequently while driving. Finally, to make the driving task more engaging and challenging, we reduced the navigation marker changing position time between lanes to 7 seconds.

Results of Pilot Study-2: In this pilot study, we discovered the following new issues. First, without looking, it was difficult to locate the centre (starting interaction point) on the web stencil. While looking for the centre, subjects made unintentional touches to other parts of the touchscreen. Even though we added texture to the centre of the web stencil to provide more tactile sensations and distinguish it from the rest of the stencil area, it was ineffective. The subjects were unable to reach the centre solely through proprioception. Second, the dragging sound we added to the marker was both irritating and distracting. Third, the target display time on the driving screen was still too long; it should be reduced to simulate more frequent touchscreen interaction. Fourth, during the testing phase, we discovered that the corner curve stencil was difficult to use, resulting in poor accuracy. Finally, dragging diagonally on the corner curves stencil was difficult; ridges on the stencil were obstructive and time-consuming. The subjects became stuck while dragging and lifted their finger from the touchscreen, retrying to hit the target. The second try on the same target lengthened the overall target selection time.

Pilot Study-3: Based on the results of Pilot Study-2, we made some additional changes to our experiment. First, we removed the *Web stencil* and the *Corner Curves stencil* from our study. The results of these stencils were unimpressive. Second, in all stencil designs, we removed the dragging sound. Third, we shortened the time it took for the first target to appear to 2.5 seconds and maintained the same time (2.5 seconds) for subsequent targets. Finally, in the training and testing phases, we reduced the number of candidate items to four in order to shorten the overall experiment length.

Results of Pilot Study-3: We discovered in this pilot study that the drag mechanism would not work on any of these stencil designs. This interaction metaphor had several flaws that we discovered. To begin, we discovered that dragging the marker on the stencil degraded driving performance due to attentional demands to drag a finger to a specific location. Second, it was time-consuming; on average, it took around 5 seconds to select one target on the *Grid* and *Nubbin* stencils, compared to only 2.5 seconds on the *Normal* touchscreen. Although target selection time was not our main concern, we have already stated that these stencil designs do not support design goal four: *Low task completion time.* However, we aim to strive for shorter task completion times because longer task completion times may result in cognitive distraction.

We changed the interaction metaphor on these stencils in response to these issues. Instead of *'drag and release'*, we decided to use the '*Span and Tap*' metaphor by utilising the nubbins on the stencil, which will be discussed further in a later section. Furthermore, the pilot studies revealed that the *Grid* and *Nubbin* stencils could provide eyes-free interaction despite a long target selection time. Subjects were able to choose the target without even looking at the touchscreen. As a result, we made the necessary changes, and in the final experiment design, we used we used *Nubbin*, *Grid* and *Normal* stencils.

3.3.3 Stencils Interaction Metaphor

As discussed in the previous section, the *Half Tap* (drag and release) we tested in pilot studies failed for a variety of reasons. As a result, we decided to switch the interaction metaphor to*Span and Tap.* The general interaction strategy was for the user to place one finger in the nubbin on the stencil, make a span, and then tap the target with the other finger. The *Span and Tap* metaphor may be applicable to these stencil designs for the following reasons. First, the nubbins on the stencil were designed to be the starting point for making a span. When a user places their finger in a nubbin, they will be able to precisely determine their hand position on the touchscreen as well as the underlying touchscreen controls in close proximity. For example, the call receive icon is located to the northeast of the 'X' nubbin. Users can be trained to select a specific icon on a touchscreen by making the same exact span from a 'X' nubbin, which could enable eyes-free target acquisition while driving. Second, it is similar to the 'tap' metaphor used on a standard touchscreen, and because of this similarity, users can learn and use this metaphor with little training. Third, it is much easier to apply the drag metaphor that we tested earlier in pilot studies.

On the Nubbin stencil, the interaction metaphor was as follows: First, the subject had to use proprioception to reach the closest nubbin to the target. If the subject was unable to locate the nubbin using only proprioception, the subject could use tactile sensations to guide their finger on the stencil in search of the nubbin. Once the nubbin was located, the subject had to keep one finger in the nubbin, make a span with the second finger, and tap on the target to complete the selection. The selection metaphor was limited to tapping only; dragging and releasing would not complete the acquisition. Repeatedly selecting the same target can improve proprioceptive, tactile, and span gesture knowledge, allowing for completely eyes-free interaction while driving.

We placed four nubbins (two circle-shaped and two square-shaped) on the nubbin stencil in such a way that the full touchscreen was accessible via the 'span and tap' interaction mechanism from these nubbins. Because each nubbin on the stencil has a distinct tactile sensation and location on the stencil, the subject could easily distinguish between nubbins. On the right side of the stencil, for example, the square nubbin is on top and the circle is on the bottom, and vice versa on the left side of the stencil.

On the Grid stencil, the subjects had to first use proprioception to locate the bezel of the stencil (the part closest to the target). The subjects then use tactile sensation to guide their finger to the nubbin closest to the target. After locating the nubbin, the subject had to keep one finger in the nubbin while making a span with the other finger to tap the target to complete the selection. Similarly, the target selection metaphor was limited to only tapping. With practise, the user could make precise span and tap gestures on the touchscreen for a specific target without the need for visual guidance. Sixteen nubbins (4 on each bezel) on the Grid stencil can be used as a starting point for touchscreen interaction. Placing four nubbins on each side of the stencil allows you to reach every part of a touchscreen using the 'span and tap' interaction mechanism.

The interface layout was consistent across all display conditions. In a grid format, twenty icons were displayed. To avoid learning bias from other display conditions, we used a different set of icons in each display interface. Acoustic feedback has been added to these interfaces. When a target was successfully selected, a 'Pling' sound was played, a 'Buzz' sound was played, and a 'Beep' sound was played when an error occurred (wrong target and lift-off), and a 'Beep' sound was played when a target appeared on the driving screen. When the user made contact with any icon on the touchscreen, we added a beep sound. When the subject is not looking at the touchscreen, this beep sound may help them select a target.

3.3.4 Experiment Setup

The experiment was carried out in a contained environment at a local university. The driving simulation setup is showed in Figure 3.12a. The subjects sat in a standard office chair, while a driving simulator was displayed on a screen in front of them, and a touchscreen was mounted on the left side of the steering wheel. Because the touchscreen was mounted on the left side of the steering wheel, 90% of the participants could have used their non-dominant hand to interact with the touchscreens (as approximately 90% of the human population is right hand dominant [65], [79]). We did not record the participants' dominant hand. Because touchscreens are located to the left of the steering wheel in right-hand drive vehicles, it was irrelevant to our study.

We used three display conditions in this experiment: normal touchscreen, grid stencil, and nubbin stencil. Each display condition had four phases: practice, training, visible testing, and invisible testing. The experiment's testing-invisible phase was based on hidden target selection, in which the targets were hidden on the touchscreen and the subject had to select the target without looking at all.

We anticipated that the normal touchscreen would initially be faster and more accurate than the stencils, but that as users gained experience with them, the stencils would achieve similar task completion time and accuracy. Similarly, we hoped that by using the stencils, users would be able to reduce their reliance on gaze-directed selection, eventually completing selections eyes-free.

3.3.5 Subjects and Apparatus

Eighteen undergraduate and postgraduate students were recruited for the experiment from a local university. They had all had a valid driving licence for at least a year. All of the subjects were used to interacting with touchscreens. As a reward for participating in the study, subjects were given a $10 cafe voucher.

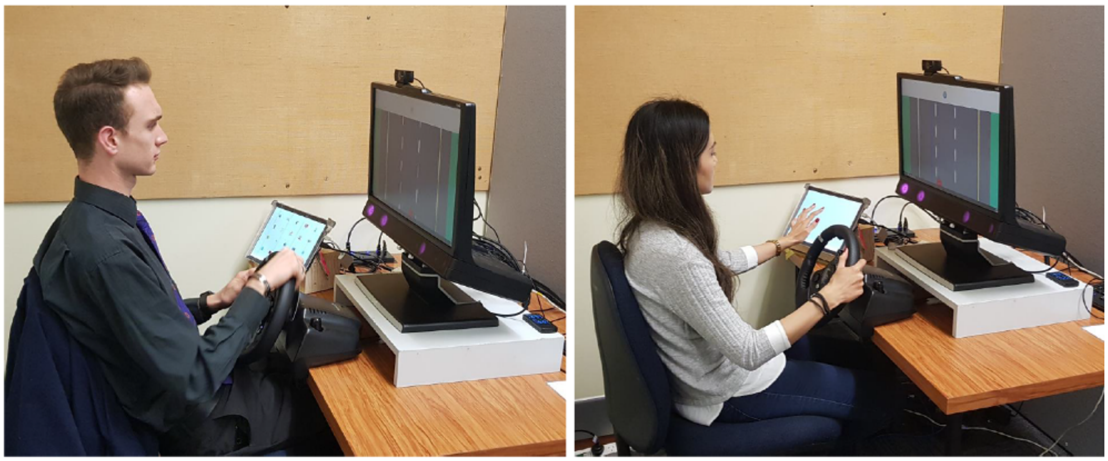


Figure 3.19: Subjects involved in experiment of Study-I.

The subjects drove the car using a 'Logitech G29' steering wheel. For eye-tracking and displaying a driving simulator, we used a 'Tobii Pro TX300' with a 24" 1080p display. The Tobii eye-tracker had its own display above the sensors, which we used to show the driving simulator and to organise the experimental equipment. A 12.3" Microsoft Surface Pro (2736 × 1824 pixels, 267 PPI) installed on the left side of the steering wheel received touch input. For all subjects, all equipment was fixed and remained in the same position. However, at the start of the experiment, subjects were asked to adjust the position of the chair to their comfort level within the range of the eye tracker, and then they were asked to remain still after eye calibration.

To mount the stencils on the touchscreen, we printed four locks, one for each corner, as shown in Figure 3.20, These locks kept the stencils firmly in place on the touchscreen and made changing them quick and simple. We created a wooden stand, as shown in Figure 3.21 and used several 'Velcro strips' on the table to secure the stand's position.

Figure 3.20: Locks used to mount stencils on the touchscreen.

Figure 3.21: Wooden stand used to fix touchscreen on the table.

3.3.6 Experiment Design

The experiment used the following within-subjects factors:

- display type ∈ {*normal, grid, nubbin*}
- block ∈ {*p1..p2, tr0..tr6, tev7..tev9, tei10..tei12*}

P1..p2 are practice blocks, tr0..tr6 are training blocks, tev7..tev9 are testing-visible blocks and tei10..tei12 are testing-invisible blocks. The following dependent measures were taken: gaze-away time, driving path deviation, error rate, and target selection time. Gaze away time was the total time the subject spent looking anywhere than at the driving screen when the target appeared on the driving screen and selected by the subject on the touchscreen. Path deviation was measured as the absolute difference (in pixels) between the ideal path marker and the car position when the target appeared on the screen and selected by the subject on the touchscreen. Errors were recorded for the following conditions: the wrong target and lift off. Target selection time was the total time from when the target was displayed and when the subject attempted to select. User actions were recorded automatically by Python logging script and eye-gaze data by using 'Tobii Studio' software.

The subjects were divided into three groups, each with six subjects. A Latin square was used to balance the display type order. On each display type, each subject had four targets. Each subject made 96 target selections in one display type, for a total of 288, as shown below.

- *practice*: 16 selections (data discarded)
- *training*: 56 selections
- *testing-visible*: 12 selections
- *testing-invisible*: 12 selections

Targets were generated at random for each subject, so each subject chose a different set of targets in each display condition. Each target was chosen in a counterbalanced order.

During the practice and training phases, each target was selected twice sequentially, first visible and then hidden on the touchscreen. In the experiment, we used this technique to see if tactile sensations on stencil overlays can help subjects choose targets when visual feedback is completely absent. We tested invisible target selections in the (testing-invisible phase), where icons on the touchscreen were hidden and subjects had to select the target using only proprioception and tactile sensation.

3.3.7 Procedure

The experimenter introduced the subjects to the experimental procedure. At the start of each display condition, subjects were briefed and trained on the target selection mechanism and driving task. The primary goal of the experiment was to drive the car with a steering wheel 'as close to the blue navigation marker as possible'. The experiment's secondary task was to select the cue of targers 'as quickly and accurately' as possible on the touchscreen that appeared at the top centre of the driving screen.

While the subjects were driving, a beep sound was played to alert them that a new target needed to be selected on the touchscreen, with the target icon displayed at the top of the driving display (see Figure 3.12a). On successful or unsuccessful selection, the target icon disappeared from the driving screen, and a new target appeared after 2.5 seconds. The subject only had one attempt to select the target; if an error occurred, the target icon disappeared from the driving screen, and the next target was displayed. Due to the hidden target selection, we limited the target selection attempt to one. Repeated attempts to select hidden targets may lead to fatigue, frustration, and an increase in overall experiment time. The fatigue and frustration caused by one display condition may have an impact on the results of other display conditions. Furthermore, the lack of visual feedback on the touchscreen may demotivate subjects if they repeatedly fail to select a target, affecting overall performance. As a result, we limited the target selection to one attempt. The experiment phases are presented as follows:

In the practise phase, the subject selected four icons, twice each. On the touchscreen, the target was first visible, and then it was hidden. The toggle between visible and invisible was intended to train subjects to use physical augmentations on stencils in the absence of visual feedback. Subjects completed 16 selections in 2 blocks, 8 targets in each block.

In the Training phase, 20 icons were used, and 4 of them were selected as targets. Similarly to the practise phase, the subject was required to select the target icon twice in a row (visible and invisible). One subject completed 56 selections in 7 blocks, each with 8 targets.

The same 20 icons from the training phase were used in the Testing-visible and Testing-invisible phases, as well as the same four target icons. During the testing-visible phase, target icons were visible on the touchscreen at all times, and the subject had to select each target once. During the testing-invisible phase, target icons were always hidden on the touchscreen. In each phase, the subject completed 12 selections in three blocks of four selections each.

Once the subject had completed all 96 selections of the first display condition (16 — practice, 56 — training, 12 — testing-visible, and 12 — testing-invisible), a NASA-TLX [34] (Appendix D) workload sheet was given to rate the display condition. The experimenter removed the current stencil and attached the next stencil for the next display condition while the subject was filling out the sheet. After that, the subject was instructed on the next target selection technique and went through the same four-phase procedure as described above. This procedure was repeated until all three display conditions had been assessed. Finally, subjects filled out a preference-based sheet, rating each display condition from best to worst (Appendix E).

3.3.8 Data Analysis

We gathered experiment data from two different sources. Tobii studio software recorded eye gaze data, while touchscreen interaction logs recorded task completion time, errors, and driving performance. We wrote Python scripts to merge and align two different data sets. These files were merged using scripts based on UTC (Coordinated Universal Time) time stamps. To analyse experimental data, we used R scripts.

Chapter 4

Results of Layout-agnostic Stencils

This chapter presents the outcomes of Study-I: Examine the design and use of layout agnostic stencil overlays for in-vehicle touchscreens. The chapter is divided into two sections: the first presents statistical results, and the second presents a discussion based on the results.

4.1 Results

TextbfH1: The attentional demands required by in-vehicle touchscreens while driving can be reduced with layout-agnostic stencils was the main hypothesis of Study-I. For each measure considered, the H1 was further subdivided as follows. Once the user is expert of using touchscreens with layout-agnostic stencil overlays, it would:

- H_{vd} - reduce visual attentional demands
- H_{pd} - reduce path deviation
- H_{re} - reduce errors
- H_{ts} - reduce target selection time

The following subsections present the results separately for each of the hypotheses. We are testing the main hypothesis **(H1)** with the results of the *Testing-visible* phase of this experiment. However, we are also curious to see the results of *Training* and *Testing-invisible* phase; therefore, those results are also presented. We were curious to see how the subjects behaved during the training phase and *testing-invisible* phase when there was no visual feedback on the touchscreen and there was no point of looking at the touchscreen. In the statistical analyses, floating-point values for degrees of freedom arise from the use of Greenhouse-Geisser corrections for sphericity violations (detected with Mauchley's tests)

4.1.1 Visual Attention

This section presents the results of mean gaze-away time. Gaze-away time is when the target appeared on the driving screen and is selected by the subject on the touchscreen.

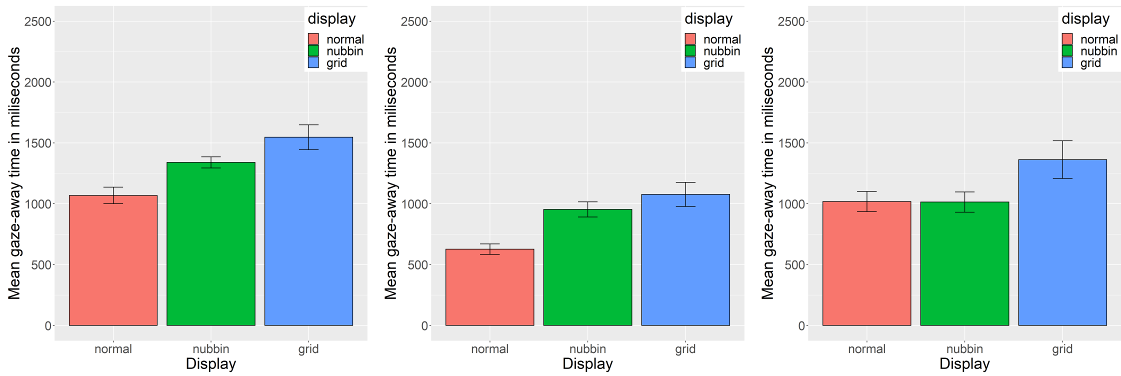
Figure 4.1a summarizes the results of *Training* phase. There was significant main effect of display type ($F_{1.54,26.25} = 14.96, p = 2.1 \times 10^{-5}, \eta^2 = 0.28$), where Normal touchscreen was less visually demanding with mean of 1067 ms (s.d., 288), compared to Nubbin stencil with a mean of 1339 ms (s.d., 192) and Grid stencil with a mean of 1546 ms (s.d., 434).

Figure 4.1b summarises the results of *Testing-visible* phase. There was a significant main effect of display type, ($F_{1.55,26.45} = 15.28, p = 1.84 \times 10^{-5}, \eta^2 = 0.29$). Contrary to our expected results, the Normal touchscreen was less visually demanding with a mean of 626 ms (s.d., 181), compared to Nubbin stencil with a mean of 953 ms (s.d., 263) and Grid stencil with a mean of 1076 ms (s.d., 419).

Figure 4.1c summarizes the results of *Testing-invisible* phase. As suggested by this figure there was significant main effect of display type ($F_{1.07,18.19} = 5.04, p = 0.01, \eta^2 = 0.11$). Normal touchscreen had a mean gaze-away time of 1017 ms (s.d., 350), Nubbin stencil also had the lowest gaze-away time with a mean of 1013 ms (s.d., 350), and Nubbin stencil has the highest gaze-away time, with a mean of 1362 ms (s.d., 658). It can be observed that when the icons were hidden on the touchscreen, the mean gaze-away time for the Normal touchscreen has significantly increased from *testing-visible* phase, whereas the Nubbin stencil had a similar gaze-away time.

The results of the *testing-invisible* phase indicate that the physical landmarks on the stencil (nubbins) aided in target selection. When targets were hidden on the Nubbin stencil, subjects used physical landmarks (nubbins) to determine the approximate location of the target on the touchscreen. The 'X' target, for example, was on the left side of nubbin 'Y.' In contrast, on a normal touchscreen, they glanced and were unable to determine the exact location of the target due to the lack of visual feedback, and there was no point in looking at the touchscreen when visual feedback was lacking unless they were guessing the location of targets by associating them with other physical landmarks (e.g., distance from target and bezel of display). They spent more time looking at the touchscreen to determine the approximate location of the target, which increased their gaze-away time. These findings suggest that when visual feedback was unavailable, physical landmarks aided in target selection.

Based on the results of *testing-visible* phase, we therefore failing to support H_{vd} – that layout-agnostic stencils can reduce visual attentional demands. The visual attentional demands on the Normal touchscreen was significantly lower as compared to both stencil overlays, showing opposite results of the desired effect.



(a) Training phase (b) Testing-visible phase (c) Testing-invisible phase

Figure 4.1: Visual attention results, showing mean times that eyes were away from the driving display. Error bars showing standard errors.

4.1.2 Driving Performance

This section presents the driving performance results. We analysed driving performance with three measures, presented as follows.

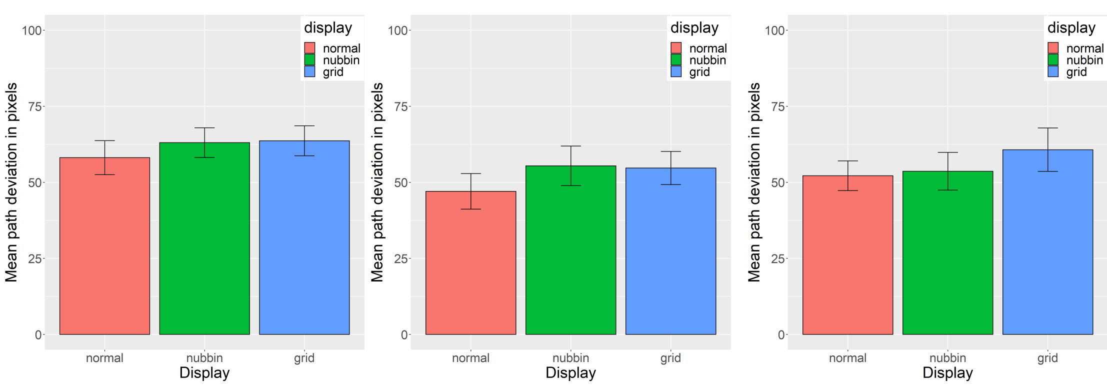
4.1.2.1 Mean Path Deviation

This section summarizes the mean path deviation. Mean path deviation is the pixel distance between the car and the navigation marker when the target appeared on the driving screen and selected by the subject on the touchscreen.

Figure 4.2a summarizes the results of *Training* phase. There was no significant main effect of display type ($F_{2,34} = 0.75, p = 0.47, \eta^2 = 0.01$). The mean path deviation for the Normal touchscreen was 58 px (s.d., 23), 63 px (s.d., 20) for Nubbin stencil, and 63 px (s.d., 20) for Grid stencil.

Figure 4.2b summarizes the results of *Testing-visible* phase. Mean path deviation on the Normal touchscreen was low as compared to both stencil overlays, contrary to our expected outcome. The mean for Normal touchscreen was 45 px (s.d., 25), compared to 55 px (s.d., 28) with nubbin stencil and 54 px (s.d., 23) with grid stencil. However, no significant effect of display type was observed ($F_{2,34} = 1.18, p = 0.31, \eta^2 = 0.02$).

Figure 4.2c summarizes the results of *Testing-invisible* phase. Similarly, there was no significant main effect of display type observed in testing-visible phase ($F_{2,34} = 1.38, p = 0.26, \eta^2 = 0.02$). The mean path deviation on Normal touchscreen was 52 px (s.d., 20), 53 px (s.d., 26) for Nubbin stencil, and 60 px (s.d., 30) using Grid stencil. The mean path deviation has increased for Normal touchscreen and Grid stencil and remained decrease for Nubbin stencil as compared to the *testing-visible* phase. The increase in the mean path deviation when icons were hidden shows the visual distraction for the primary task has increased; the gaze-away results of the testing-visible phase can support this.



(a) Training (b) Testing-Visible (c) Testing-Invisible

Figure 4.2: Mean path deviation (pixel distance between the car and the navigation marker while target is shown on the driving display). Error bars showing standard errors.

In all three phases of the experiment, there is no significant difference in mean path deviation. Our driving results, like previous studies, failed to show any significant difference in mean path deviation. We expected to see meaningful results because, in comparison to LCT and OFT, our driving simulator was designed for more sensitive driving accuracy. Prior driving simulators, for example, had an ambiguity regarding path deviation; movement away from the centre of the lane may represent a lack of driving control and may affect driving simulation results. As a result, in our simulator, subjects must precisely position their car (tip of triangle on car, as shown in 3.13) on the centre of the navigation marker. However, our findings yielded the same result. It is likely that the mean path deviation may not be a proper measure to analyse driving performance, therefore we have analysed driving performance with two other measures, presented as follows.

4.1.2.2 Maximum Path Deviation

Another measure for evaluating driving performance is maximum path deviation. The maximum path deviation is the maximum pixel difference between the car and the navigation marker when the target appears on the driving screen and is selected by the subject on the touchscreen. This measure can be used to determine how far the car moved away from the navigation marker when the subjects attempted to select the target, thereby demonstrating driving performance. The results of the mean of maximum path deviation are summarised in Figure 4.3. We recorded the maximum path deviation for each target and then calculated the mean for each display phase.

Figure 4.3a summarizes the results of Max path deviation of *Training* phase, showing no significant main effect of display type ($F_{2,34} = 2.20, p = 0.12, \eta^2 = 0.03$), ranging from 96 px (s.d., 32) for Normal touchscreen, through 106 px (s.d., 29) on Nubbin stencil, to 110 px (s.d., 29) on Grid stencil.

Figure 4.3b summarizes the results of *Testing-visible* phase, showing significant main effect of display type ($F_{1.94,33.07} = 3.89, p = 0.03, \eta^2 = 0.07$). Contrary to our expected results, the driving performance with Normal touchscreen was significantly better with a mean of 70 px (s.d., 32), compared to Nubbin stencil with a mean of 93 px (s.d., 41) and Grid stencil with mean of 91 px (s.d., 38).

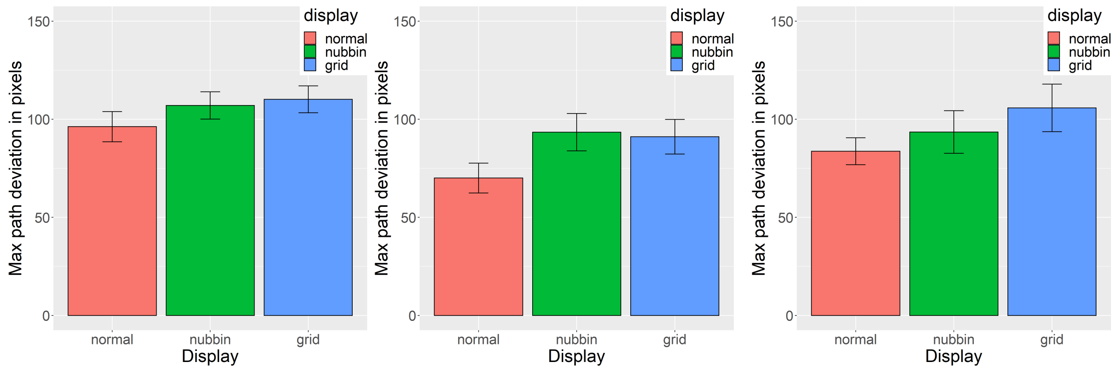
Figure 4.3c summarizes the results of *Testing-invisible* phase, showing no significant main effect of display type ($F_{2,34} = 2.55, p = 0.09, \eta^2 = 0.04$), with mean of 83 px (s.d., 29) for Normal touchscreen, 93 px (s.d., 46) for Nubbin stencil, and 105 px (s.d., 51) for Grid stencil. It can be observed that the max path deviation on Normal touchscreen has increased in *testing-invisible* phase to 83 px from 70 px in *testing-visible* phase. The possible reason for this change is that the subjects spent more time looking away from the driving screen. The hidden targets on the touchscreen increases visual attention of touchscreen. This can be supported by visual attention results of *testing-visible* and *testing-invisible* phases, as shown in Figure 4.1b and 4.1c.

The reason for this is the increase in visual attention demands when the icons were hidden on the touchscreen, as discussed in visual attention results. The increase in visual attention demands has degraded the driving performance.

The result shows a significant effect of display type in **testing-visible** phase. Contrary to our results, the driving performance was better using the Normal touchscreen. Therefore, failing to support H_{pd} – that stencil overlays can reduce path deviation.

4.1.2.3 Driving Variance Across Time

Driving variance across time is the third measure we used to analyse the driving performance. These results show the variance of path deviation when the target



(a) Training (b) Testing-Visible (c) Testing-Invisible

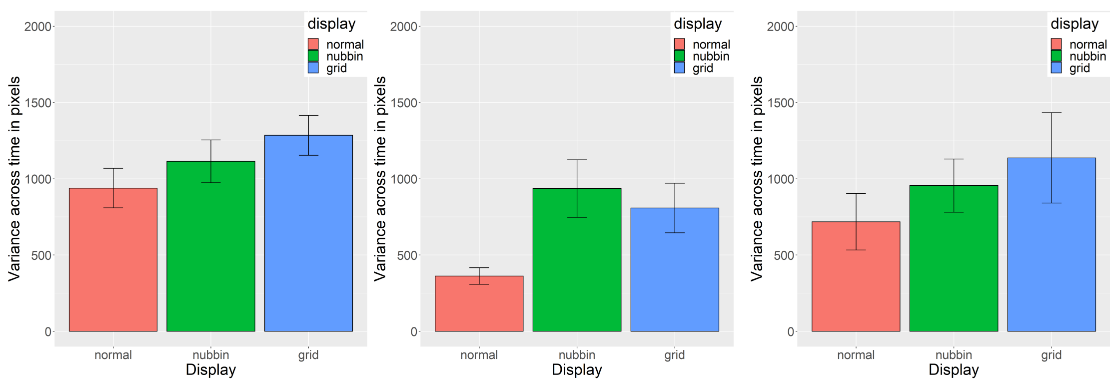
Figure 4.3: Maximum path deviation (max pixel difference between the car and the navigation market while a target is shows on the driving display). Error bars showing standard errors.

was displayed on the driving screen and selected by the subjects on the touchscreen. With the measure, we can see the variance of path deviation from the mean.

Figure 4.4a summarizes the results of *Training* phase showing significant main effect of display type ($F_{1.89,32.19} = 3.65, p = 0.03, \eta^2 = 0.06$). The driving performance on the Normal touchscreen was better with a mean of 938 px (s.d., 550) as compared to Nubbin stencil with a mean of 1114 px (s.d., 595), and Grid stencil with a mean of 1284 px (s.d., 555).

Figure 4.4b summarizes the results of *Testing-visible* phase showing significant main effect of display type ($F_{1.60,27.31} = 7.80, p = 0.001, \eta^2 = 0.14$). Contrary to our expected results, the driving performance with Normal touchscreen was much better with a mean of 362 px (s.d., 231), compared to Nubbin stencil with a mean of 936 px (s.d., 801) and for Grid stencil with a mean of 808 px (s.d., 689).

Figure 4.4c summarizes the results of *Testing-invisible* phase showing no significant main effect of display type ($F_{2,34} = 1.09, p = 0.34, \eta^2 = 0.03$). The driving performance on the Normal touchscreen was better with a mean of 718 px (s.d., 787) as compared to the Nubbin stencil with a mean of 955 px (s.d., 740) and Grid stencil with a mean of 1137 px (s.d., 1257). However, the driving performance on the Normal touchscreen degraded in this phase, as compared to the *testing-visible* phase. Similar to max path deviation, the hidden targets increase visual attentional demands of the touchscreen, which has affected the driving performance.



(a) Training (b) Testing-Visible (c) Testing-Invisible

Figure 4.4: Driving variance across time (variance of path deviation from the mean while the target is shows on the driving display). Error bars showing standard errors.

According to the findings, the mean path deviation did not show any significant difference in any of the three experiment phases, which is consistent with previous research. As a result, we examined driving performance using two new measures, and the results revealed a significant difference in the *Testing-visible* phase — that driving performance with the Normal touchscreen was superior to stencil overlays, contrary to our expectations. We therefore, failing to support H_{pd} that stencil overlays can reduce path deviation. The visual attentional demands required by stencil overlays have had an impact on driving performance. These findings are supported by visual attention findings (higher gaze-away time was observed with stencil overlays). The subjects spent more time looking at the touchscreen while selecting the targets, causing them to lose control of the car's optimal position. Whereas, on the Normal touchscreen, they needed less visual attention to select targets and were able to maintain a relatively good driving performance.

In summary, we found a significant difference in driving performance when comparing the Normal touchscreen to the stencil overlays. Three dependent variables were used (mean path dv, max path dv, and variance path dv). Similarly to previous studies' findings, mean path dv failed to demonstrate a significant difference in driving performance. In contrast, max path deviation and variance were able to demonstrate a significant difference. These findings indicate that the mean path deviation is not a suitable measure for analysing driving performance, as it failed to produce significant results in various driving simulators. As a result, we do not recommend using mean path dv to analyse driving performance. However, we recommend using Max path deviation and Variance path deviation to analyse driving performance because they are more sensitive methods. The maximum path deviation can indicate how far the car deviated from the ideal driving position while users interacted with the touchscreen. The path deviation variance can show the deviation from the ideal mean driving position.

4.1.3 Errors

The section presents the proportion of selections containing errors. Two types of errors (wrong target and lift off) were record during the experiment. The Figure 4.5 summarises the results of errors, shown in proportion (proportion ranges are shown on 0-1 scale).

Figure 4.5a summarizes the results of *Training* phase, showing no significant main effect of display type ($F_{2,34} = 1.18, p = 0.31, \eta^2 = 0.02$), with mean of 47%

error rate using Normal touchscreen, 35% for Nubbin stencil, and 35% for Grid stencil.

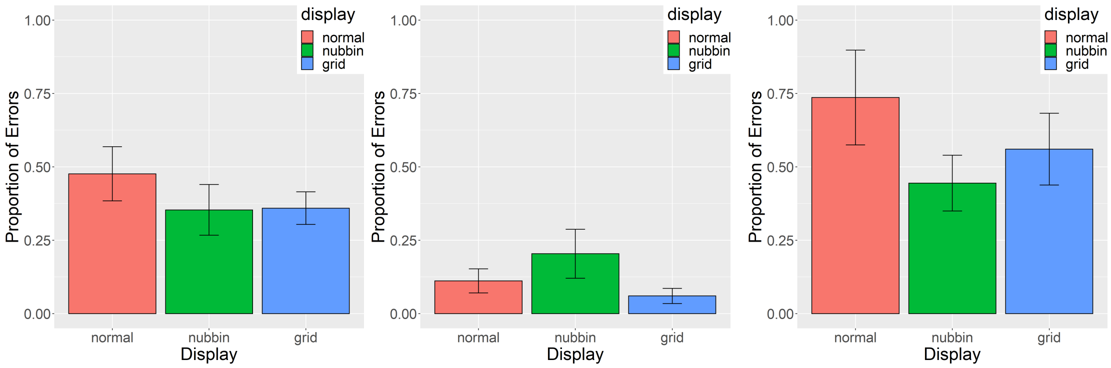
Figure 4.5b summarizes the results of *Testing-visible* phase, showing no significant main effect of display type ($F_{2,34} = 2.42, p = 0.10, \eta^2 = 0.06$), with a mean of 11% error rate using Normal, 20% for Nubbin, and 6% using Grid stencil.

Figure 4.5c summarizes the results of *Testing-invisible* phase, showing significant main effect of display type ($F_{2,34} = 1.55, p = 0.02, \eta^2 = 0.04$), with mean of 73% using Normal, 44% for Nubbin, and 56% using Grid stencil.

The results show that there is no statistically significant difference in the proportion of errors in the *testing-visible* phase. As a result, we are failing to support our hypothesis $\mathrm{H_{rd}}$ — that stencil overlays reduce errors. However, in the *testing-invisible* phase, the results show that the stencil overlays outperformed the normal touchscreen in target selection accuracy. These findings suggest that physical augmentations on stencils helped subjects estimate the location of hidden targets by making correct ‘span’ gestures when visual feedback was absent. On the contrary, because of the flat surface of the touchscreen, the subjects were unable to estimate the location of hidden targets, making them less accurate.

4.1.4 Target Selection Time

Figure 4.6 summarises the mean target selection time taken to select the target on the touchscreen, timed from the target first appeared displayed on the top of the driving screen. With these results, we can analyse how fast the subjects were able to select the correct targets on the touchscreen while driving.



(a) Training (b) Testing-Visible (c) Testing-Invisible

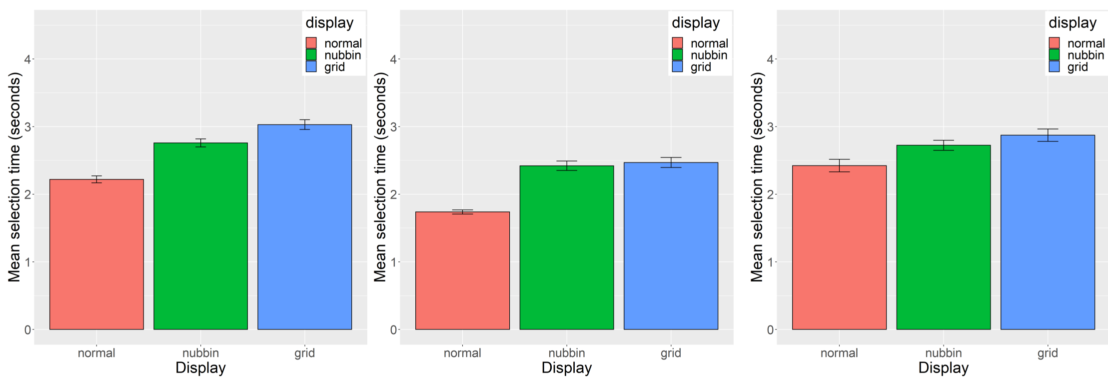
Figure 4.5: Errors (proportion of selection containing errors). Error bars showing standard errors.

Figure 4.6a summarizes the results of mean target selection time for *Training* phase. As suggested by the figure, there was a significant main effect of display type ($F_{1.67,28.55} = 24.25, p = 2.84 \times 10^{-7}, \eta^2 = 0.4$). The target selection time on the Normal touchscreen was faster with a mean of 2.22 sec (s.d., 0.58) as compared to the Nubbin stencil with a mean of 2.75 sec (s.d., 0.66) and with Grid stencil with a mean of 3.02 sec (s.d., 0.81).

Figure 4.6b summarizes the results of target selection time for *Testing-visible* phase. There was a significant main effect of display type ($F_{1.68,28.65} = 22.05, p = 7.23 \times 10^{-7}, \eta^2 = 0.4$). Similar to the training phase, the target selection time on Normal touchscreen was faster with mean of 1.73 sec (s.d., 0.23), as compared to Nubbin stencil 2.42 sec (s.d., 0.51) and Grid stencil with mean of 2.46 sec (s.d., 0.54).

Figure 4.6c summarizes the results of target selection time for *Testing-invisible* phase. Similar to the previous phases, there was a significant main effect of display type ($F_{1.91,32.50} = 5.87, p = 0.006, \eta^2 = 0.1$), with a mean selection time of 2.42

sec (s.d., 0.68) using the Normal touchscreen, 2.72 sec (s.d., 0.54) using Nubbin stencil, and 2.87 sec (s.d., 0.67) for Grid stencil.



(a) Training Phase (b) Testing-Visible Phase (c) Testing-Invisible Phase

Figure 4.6: Mean selection time (from cue appearance to correct selection). Error bars showing standard errors.

In contrast to our expectations, the results show that target selection time has a significant effect in all three phases of the experiment. The target selection time on the Normal touchscreen was faster than the target selection time on stencil overlays. As a result of these findings, we therefore, failing to support our hypothesis H textsubscriptts — that stencil overlays could reduce target selection time. Before the experiment, we predicted that the Normal touchscreen would be faster at first, but that once trained, the target selection time on stencil overlays would be faster or even the same as the Normal touchscreen. However, even after training, the target selection time was found to be relatively long when compared to the normal touchscreen. The interaction metaphor we used on the stencils ‘span and tap’ could explain these results. This interaction mechanism was time-consuming, as the subject spent a significant amount of time determining the appropriate span.

Furthermore, the target selection time in the *testing-invisible* phase was longer than in the *testing-visible* phase, particularly for the Normal touchscreen. The results show that the target selection time for the Normal touchscreen increased from 1.73 seconds to 2.42 seconds, 2.42 seconds to 2.72 seconds for the Nubbin stencil, and 2.46 seconds to 2.78 seconds for the Grid stencil. The change in interaction approach was the cause of the increase in selection time. As discussed in Section 3.3.3 of Chapter 3, when subjects made contact with any icon on the touchscreen, an acoustic feedback (a continuous beep sound) was played; it was added to assist subjects in selection when they were not looking at the touchscreen. During the *testing-invisible* phase, eight of the eighteen subjects used acoustic feedback to select hidden targets on the Normal touchscreen. Instead of tapping on the target, they moved their finger to the approximate location of the target to receive acoustic feedback before releasing the finger to complete acquisition. Although this technique increased overall target selection time, subjects were able to make more correct selections than those who did not use acoustic feedback. Those subjects who did not use this acoustic feedback had a higher overall error rate in the *testing-invisible* phase when using a normal touchscreen.

4.1.5 Subjective Responses & Observations

The subjects filled a NASA Task Load Index (NASA-TLX) sheet after completing each display condition regarding *testing-visible* phase. The NASA-TLX sheet rated each various measure within a 100-point range with 5-point steps ranging from low to high demanding. The combined mean response on NASA-TLX measure (as shown in Figure 4.7) was 42.70 (s.d., 7.57) for Normal, 46.11 (s.d., 7.16) for Nubbin stencil, and 49.65 (s.d., 5.61) for Grid stencil, indicating no significant difference between all display conditions combined (all $p > 0.21$).

Overall performance also show no significant difference ($p > 0.73$), the mean values were 51.11 (s.d, 16.85) for Normal touchscreen, 52.22 (s.d., 19.42) for Nubbin stencil, and 48.06 (s.d., 16.19) for Grid stencil. To achieve that performance level, the means values of effort were 51.67 (s.d, 25.44) for Normal touchscreen, 57.50 (s.d., 21.44) for Nubbin stencil, and 58.61 (s.d., 16.96) for Grid stencil

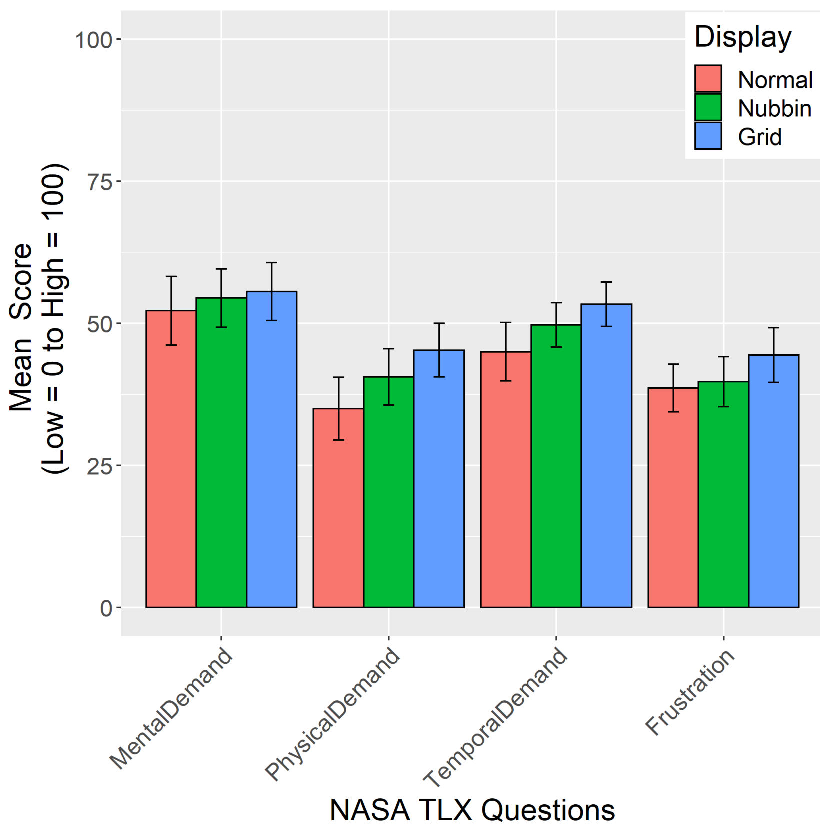


Figure 4.7: Mean responses on NASA-TLX questions.

At the end of the experiment, subjects completed a preference questionnaire sheet (rating the display from 1-Best to 3-Worst for each measure), as shown in Figure 4.8. The mean responses for all measures (combined) were 2.00 (s.d., 0.16) for Normal, 1.75 (s.d., 0.11) for Nubbin, and 2.25 (s.d., 0.08) for Grid. The results show no significant difference between all display conditions (all $p > 0.21$). The *Nubbin* stencil received higher ratings than Normal and Grid Stencil. However, the statistical results for the other dependent measures revealed a different picture: the normal touchscreen was the least visually demanding, had better driving performance, and a faster target selection time. These findings are expanded on later in the discussion section.

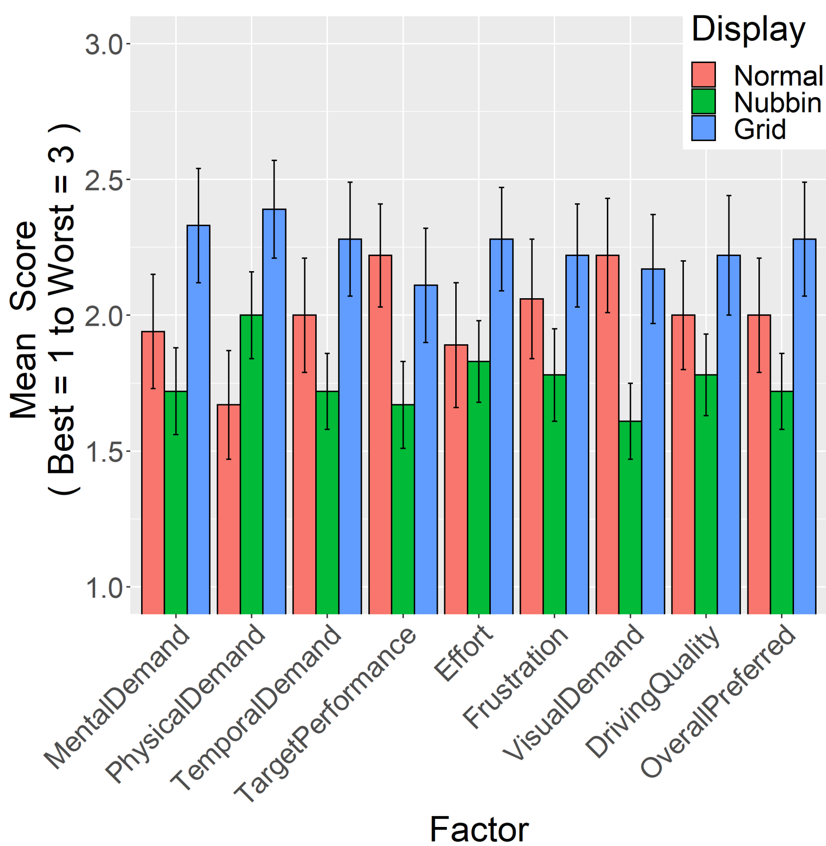


Figure 4.8: Mean score on subject's preferences questions.

Subjects also completed an open-ended response sheet to provide feedback on these interfaces. According to the comments, the subjects found *Normal* touchscreen to be the easiest to use when compared to other stencils. *S3* commented that the, *'it was a simple and known approach, as we use on our touchscreen smartphones'*, *S5* commented *'Normal was more convenient as compare to other stencils which required two-finger to select an icon'*. *S11* also reported that *'span* *and tap was difficult to use and for some targets, we had to make an awkward span position'*.

Despite their difficulty in selecting targets, subjects had positive things to say about stencils. Several subjects reported that the physical landmarks on the stencils (nubbins and grid pattern) aided in memorising the location of touchscreen icons. For example, *S3* commented, *'The Nubbins on the stencils were helpful for locating the targets'* and *'Grid pattern helped in memorising the location of icons'*. Subjects also commented that *Normal* touchscreen required more visual attentional due to the flat surface, whereas tactile pattern assisted in memorising and locating the icons without visual feedback. *S13* said *'it was difficult to select the icon with seeing it'* and *S9* commented *' difficult to memorise the location of icons due to plan surface'*. Two subjects stated that they used proprioceptive knowledge to select targets on the Normal stencil without looking.

During the experiment, the experimenter observed the subjects and took notes. It was discovered that 10 of the 18 subjects struggled to make a 'span' on stencil overlays to select the target. To acquire the target on stencil overlays, subjects had to make a span and tap with other fingers. It was discovered that they were having difficulty completing a specific span, particularly when the targets were on the bottom portion of the touchscreen. During *Training* and *testing-visible* phases, those subjects also used a different set of fingers to select an appropriate 'span and tap' gesture. They used the thumb and index finger for the target at the top of the display, for example, and a different combination of fingers for the target at the bottom of the display.

Only four of the eighteen subjects who used the *Grid* stencil used horizontal nubbins (nubbins on horizontal edges of display). The majority of the participants used vertical nubbins on both sides of the touchscreen. The experimenter also noticed that three other subjects (in addition to those mentioned above) attempted to use horizontal nubbin on the Grid stencil. However, when they encountered awkward gestures, they reverted to the vertical nubbin.

It was also discovered that when icons were hidden on the *Normal* touchscreen during the *testing-invisible* phase, 8 out of 18 subjects relied on acoustic feedback. When a subject made contact with any touchscreen control, the user interface was programmed to play a continuous beep sound. Subjects used this acoustic feedback to help them choose a hidden target. They moved their finger near the target to get acoustic feedback, then tapped on that location to complete the acquisition. This technique aided subjects in identifying hidden targets, but at the expense of target selection time. As shown in Figure 4.6c, selection time increased during the *testing-invisible* phase. In the *testing-invisible phase*, however, the majority of the subjects relied on physical augmentations to make 'span and tap' gestures on stencil overlays. This is supported by consistent target selection time in the *testing-visible* and *testing-invisible* phases for stencil overlays.

4.2 Discussion

To summarise the main findings of the experiment, subjects who used the Normal touchscreen spent less time with their gaze directed away from the primary driving task than those who used stencil overlays (failed to support H_{vd}). Driving performance on the Normal touchscreen was better to stencil overlays (ailed to support H_{pd}). The number of errors subjects made during the experiment shows no significance (failed to support H_{re}). Finally, the Normal touchscreen was faster in selecting targets than stencil overlays (failed to support H_{ts}). Based on these findings, *layout-agnostic* stencil overlays failed to reduce visual attentional demands and worsened driving performance.

4.2.1 Evidence of Intended Success of Stencil Overlays

In the display preferences question, 11 subjects rated the Nubbin stencil as having the 'best target performance' and 'least visual demanding' when compared to the Normal touchscreen. The statistical data, on the other hand, revealed completely opposite results. These contradictory results could imply that the subjects believed they could select targets accurately and without taking their gaze away from the driving display. Because of the tactile sensations on the nubbins and 'span and tap' gestures, they may have believed that the nubbins on the stencil aided them in eyes-free target selection; however, this could be true or false for the following reasons. It was discovered that the subjects required visual feedback before placing their finger on the nubbin; once they placed their one finger on the nubbin, they were able to make the correct span regarding target location and completed the acquisition. The time they spent looking at the touchscreen to place their finger on the nubbin, on the other hand, increased the overall visual demands. The results of the eye-gaze direction can support this claim.

The error rate results were another indicator of intended success. The statistical error results show a significant difference in the *Testing-invisible* phase, where the Nubbin stencil had a lower number of errors than the Normal touchscreen. Subjects found it difficult to select targets due to the lack of visual feedback and tactile sensations on the Normal touchscreen. The tactile sensations of nubbins, on the other hand, guided the subjects in selecting underlying hidden touchscreen controls. Furthermore, if they had looked at the touchscreen, the visual guidance provided by the stencil could have aided them. Because of these factors, the Nubbin stencil produced fewer errors than the Normal touchscreen and was also preferred by the subjects.

According to the preceding discussion, stencil overlays with nubbins can still reduce visual attentional demands if subjects rely solely on proprioception and tactile sensations for the entire target acquisition process, as we confirmed in pilot studies. Despite proper training and clear instructions, subjects preferred visual feedback over proprioception and tactile sensations in this study. The study is likely to have several interface design and methodological issues, which will be discussed further in later sections.

4.2.2 Methodological Issues

In the study, we identified experimental design issues. We used physically demanding steering wheel settings in the experiment. Several subjects, particularly female subjects, reported that steering the car required significant force and that proper control required two hands. Subjects were afraid to remove one hand from the steering wheel in order to select the target on the touchscreen, which influenced the overall results of other dependent measures, particularly on stencil overlays. Subjects had to tap on the target to complete acquisition on the normal touchscreen, which could be done with a quick glance and tap. They had better control over the car and were able to keep their eyes on the driving screen due to tap interaction. In contrast, they had to make 'span and tap' gestures to acquire the target on the stencils, which required more physical and visual contact with the stencils, affecting driving performance, target selection time, and accuracy.

4.2.3 Summary

Prior research on *Layout-specific* stencils promised to aid in-vehicle touchscreen interaction [13], [15], [43], [47], [92]. Those stencils, however, were limited to a single underlying user interface. To address this limitation of previous stencils, we developed several design goals and iteratively designed and evaluated several layout-agnostic stencils. Our findings revealed that layout-agnostic stencils failed to reduce visual attentional demands and improve driving performance. We examined our findings and discovered evidence of the intended success of layout-agnostic stencils, as well as several functional and methodological flaws in our study.

We proposed a framework to further investigate why our layout-agnostic stencils failed. We used the framework to further evaluate the experiment results and discovered some interesting insights, which are presented in Chapter 5 of this thesis.

Chapter 5

In-vehicle Dashboard Interaction Framework

Previous research suggested that layout-specific stencils could reduce visual attention demands while driving. With our best efforts, knowledge, and understanding of human factors, we iteratively designed and evaluated several layout-agnostic stencils. We were adamant about seeing positive results. Our layout-independent stencils, on the other hand, failed to reduce visual attentional demands and improve driving performance. Our stencils' failure indicates that we most likely overlooked some critical human factors while designing and evaluating layout-agnostic stencils for in-vehicle touchscreens while driving. We still do not know how humans interact with dashboard controls while driving. In this regard, we proposed a framework to critically analyse experimental results and understand the in-vehicle dashboard interaction in order to better understand human-dashboard interaction while driving.

5.1 The Framework

The proposed framework (shown in 5.1) is inspired by Card, Moran, and Newell's "Human Information Processor" model [11]. This framework, on the other hand, is distinct from other frameworks available in the literature. For example, Card, Moran, and Newell's "Human Information Processor" model was designed for a single attention task; they did not consider dual-attention tasks when developing their framework. When compared to dual-attention tasks, the factors associated with and information processing with single-attention tasks are significantly different. In a single-attention task, the user's entire attention is directed on one task; in a dual-attention task, the attention is diverted from one task to the other, resulting in distraction and poor performance on one of the tasks. Prior frameworks did not take this into account. Our framework emphasises human factors associated with dual-attention demanding tasks (for example, interacting with dashboard controls while driving a car), which are both cognitive, visual, and physical demanding activities.

There is a lack of clarity in the literature about what factors are associated with dual-attention demanding tasks and how humans process information in such activities. As a result, our layout-agnostic stencils failed to reduce visual attentional demands because we clearly lacked some critical knowledge when designing layout-agnostic stencils. Therefore, understanding this was critical in order to address the current issues with in-vehicle touchscreens. We proposed a framework in this regard. The framework describes human factors associated with dashboard controls as well as how humans process information related to those factors. To the best of our knowledge, this framework is unique in that it is the only one that presents the human factors associated with dual-attention demanding tasks.

The framework proposed here could be useful for the following purposes. First, it could be helpful to better understand low-level human activities with in-vehicle dashboard controls. The framework describes human factors associated with dashboard controls as well as how humans process information related to those factors. Second, it could be used to evaluate in-vehicle dashboard interaction while driving. The framework depicts the steps/process of dashboard interaction while driving; each of these interaction steps can be used to evaluate previous studies. Third, it could assist car manufacturers and researchers design new systems that are less visually demanding and less distracting. For example, car manufacturers can refer to the framework to understand what factors they need to focus on in order to reduce visual demands when designing new interaction methods that are less visually demanding.

The framework is divided into four sections: Cognitive information for execution, Visual information for execution, Execution (Motor Process) and Cognitive evaluation. The framework was designed in this order because this is how humans process information when interacting with vehicle dashboard controls. For example, the first interaction step recalls information needed to complete the task; the second is acquiring/recalling visual information; this can also be used in conjunction with the third step, Execution. After acquiring cognitive and visual information, humans use that information to execute the task (motor process), and the fourth step is cognitive evaluation, in which humans evaluate their actions based on the outcome of execution.

5.1.1 Cognitive information for Execution

The first phase of a driver's interaction with in-vehicle controls is cognitive information needed to complete a task. Cognitive information includes task conception

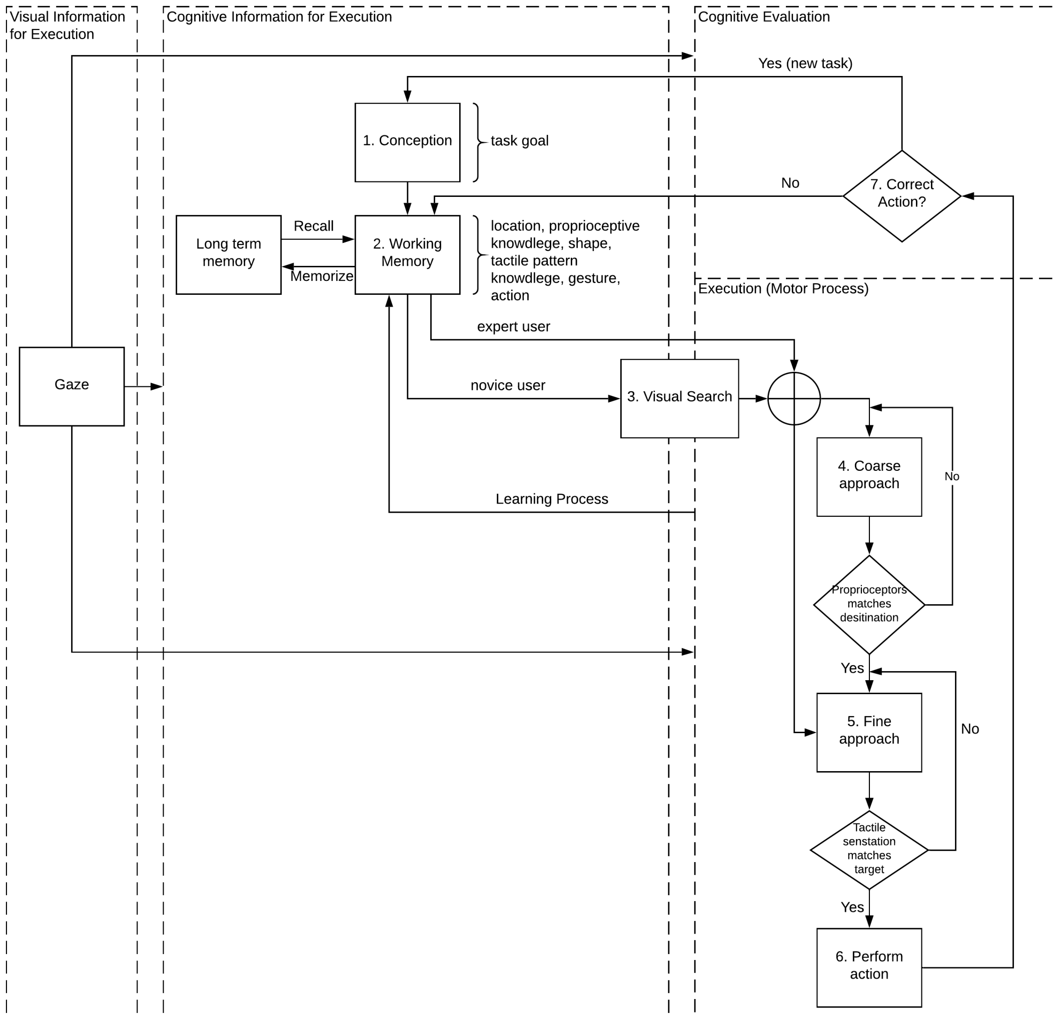


Figure 5.1: In-vehicle dashboard interaction framework.

and recalling prior knowledge and experience from in-vehicle controls into working memory from long-term memory.

5.1.1.1 Conception

Conception is the first step in the interaction process with in-vehicle controls. Conception is defined as a driver's mental activity to determine a task. A driver is likely to perform various tasks on the dashboard as needed while driving a vehicle.

For example, if the volume of a music player is too low to hear, the driver conceives a task to increase the volume of a music player.

5.1.1.2 Working Memory

Traditional memory is divided into two types: short-term memory (also known as working memory) and long-term memory [90]. The working memory holds information for a few seconds to a few minutes. Long-term memory holds information for hours, years, or even a lifetime [84]. In-vehicle dashboards have several functions, and memory is essential for using those functions. For example, in order to use the dashboard function effectively and efficiently, we need to memorise its purpose, usage, and location for future reference. Assume we do not know the purpose, usage, or location (e.g., first-time experience). In that case, it could be a time-consuming and inefficient approach.

Once the task has been conceived, the driver will recall the information associated with the task from long-term memory to working memory in order to perform the action on the dashboard. Working memory may contain information such as the location of a control on a dashboard, proprioceptive knowledge, shape of control, tactile pattern knowledge, gesture, and action to complete the task.

Since the novice user has little experience with the system, he or she may lack adequate system knowledge. However, the novice user may recall a similar interaction they have had on other systems. For example, suppose the task is to increase the volume of a music player. The driver may recall some prior knowledge, such as the location of the volume control on the other systems, the shape of the volume control, the tactile pattern of the control, and the action required to increase the volume. As a result, because most vehicle manufacturers use a generic form of controls, the novice user can apply prior knowledge of other systems. On a tradi-

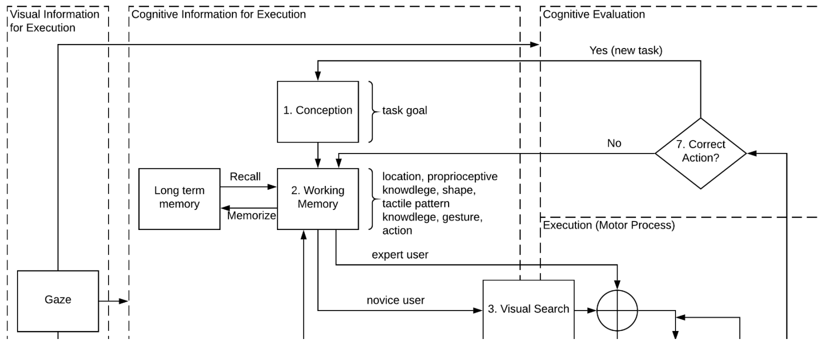


Figure 5.2: Framework showing parallel requirement of visual information with other components.

tional dashboard, for example, the volume of the music player is controlled by a 'rotating knob.'

Since the expert has prior experience with the system, he or she is more likely to recall the following types of information into working memory: the location of the control on the dashboard, proprioceptive knowledge, the shape of the control, tactile pattern knowledge, gesture, and the action required to complete the task. For example, the volume control knob was located in the top right corner of the infotainment system, was round in shape, and had tactile patterns, and rotating it clockwise increased the volume.

5.1.2 Visual Information for Execution

Visual information required to interact with in-vehicle controls is another segment of the interaction. Users may require visual information at any time during their execution, as illustrated in Figure 5.2. As a result, the visual information component is displayed concurrently with all other interaction phases. Subjects, for example, may require visual guidance to confirm the location of a control on the dashboard or visual feedback while performing and completing the task.

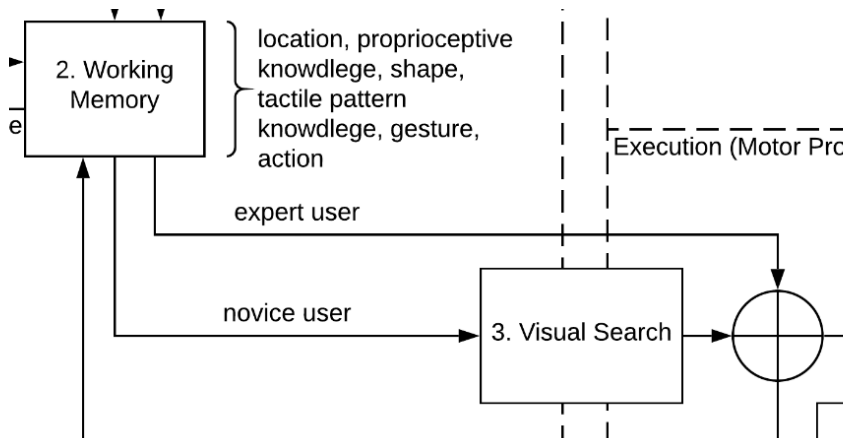


Figure 5.3: Framework showing expert user can skip visual search.

5.1.2.1 Visual Search

Once the user has recalled prior cognitive information into working memory in order to perform the conceived task, the novice user is likely to conduct a visual search on the dashboard to obtain information about the location of the desired control on the dashboard.

The expert user is not expected to perform the visual search because the user is already familiar with the system. As a result, the expert user can skip the visual search and proceed directly to the execution, as shown in Figure 5.3.

5.1.3 Execution (Motor Process)

In general, the driver will attempt to execute the task if he or she has sufficient cognitive and visual information about it. In this framework, the execution phase is described as a muscular activity of body parts (particularly the driver's hand) to perform an action on a dashboard. The execution phase is divided into three steps that involve various proprioceptive and sensory actions: coarse approach, fine approach, and perform action. The driver will learn and memorise the actions they have performed thus far (as shown in Figure 5.1, an arrow connected to the working memory phase), and the novice user will gain expertise in due course.

5.1.3.1 Coarse Approach

The coarse approach here refers to open-loop movement control based on Fitt's Law [73]. An open-loop control is defined as a rapid movement of a body part without receiving feedback, such as grabbing the steering wheel quickly. The driver moves the hand quickly towards the target (a control), and the speed decreases as the hand approaches the control. Some in-vehicle controls, such as grabbing the gear lever or the steering wheel, are likely to be obtained only through coarse movement. It is determined by the size, height, and shape of the in-car controls.

5.1.3.2 Fine Approach

The fine approach here refers to closed-loop movement control based on Fitt's Law [73]. A closed-loop control is a movement of a body part with feedback. Adjust the hands on the steering wheel, for example. The fine movement is a slower movement of the driver's hand used to search for the desired control using tactile sensation. The driver may get a tactile sensation from some controls on the dashboard with each slower movement. Some controls or the surface of the dashboard may lack texture or pattern to provide tactile sensations to the driver. The tactile sensation received from other controls may assist the driver in correcting their actions until they reach the target control.

5.1.3.3 Perform Action

The perform action refers to the gesture that the driver needs to make on the dashboard control. For instance, pressing a button or turning a knob. Once the driver has found the desired control using the fine approach, the driver will act to complete the task. The information (e.g., location, shape, tactile sensations, action) for the conceived task has already been recalled into working memory by the driver. For example, suppose the task is to increase the volume of the music player. Assuming the music player volume control is a physical knob, turning it clockwise will increase the volume.

5.1.4 Cognitive Evaluation

Cognitive evaluation is the final phase of interaction in which the user determines the success of the action performed. To increase the volume of a music player, for example, the action was to turn the volume control knob clockwise. The user will now determine whether the volume has increased or not.

5.1.4.1 Correct Action?

The user evaluates the performed action based on the system's feedback. Dashboard controls in vehicles provide feedback in a variety of forms, including visual, acoustic, and tactile. The most common forms of feedback on a touchscreen are visual and acoustic. On physical dashboard controls, tactile and acoustic feedback is common.

Once the driver receives feedback from the system, the driver will evaluate the performed action and memorise the steps performed during the previous task (as shown in Figure 5.4, a connection from '7. Correct actions' to 1. Conception' and '2. Working Memory'). The driver could evaluate the action both during and after it was completed. Increasing the volume of the music player, for example, is a continuous action; the driver is likely to evaluate the action while carrying out the task (the change in volume level until reaching the desired level). The driver may evaluate the action at the end of the interaction for other controls. For example,

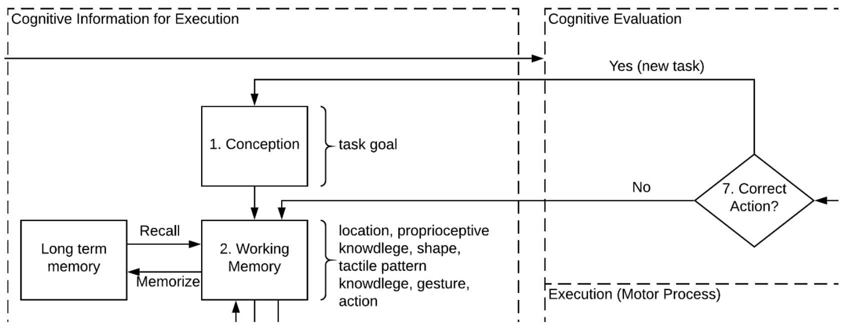


Figure 5.4: Framework showing the driver memorising steps performed in last task.

pressing a button to change the music track; if the track changes, the action was successful.

If the feedback is positive (correct action), the driver will proceed to perform the new task as needed, beginning with the framework's conception phase, as shown in Figure 5.4. Assume the feedback is inconsistent with the desired outcome. In that case, the driver will retry the last attempt, repeating steps from the framework's working memory phase with some adjustments.

5.2 Evaluation of Results from Study-I with Framework

The framework above provides a useful lens for assessing the interaction problems that contributed to the failure of our layout agnostic stencils. We analysed our experiment results, observations, and post-experiment feedback using the framework.

We analysed our results for each step of the framework, which consisted of several in-vehicle interaction steps. For example, the first interaction step was 'Conception,' and we identified all of the problems associated with the interaction's conception step. We repeated this process for each interaction step until we identified all significant problems with the interaction design. We have classified these issues as interface design failures and experimental design. We identified three major interface design flaws, which are mentioned below.

5.2.1 Coarse Approach Failure

We expected subjects to use proprioception to reach the first features of stencils (e.g., nubbins). However, we found that subjects were unable to reach the target's approximate location using proprioception. When subjects struggled with proprioception, they relied on visual information, as shown in Figure 5.1, '3. Visual search'. The use of visual information caused visual distraction from the driving task and increased the time spent looking away from the primary display (driving screen).

The size and shape of nubbins on layout-agnostic stencils could be a factor in the coarse approach failure. The nubbins we used on stencils were too small to reach with just proprioception. As previously stated, we can easily grasp large vehicle controls like the gear lever, steering wheel, and handbrake. Subjects, on the other hand, were unable to reach nubbins on stencils.

We believe there is a knowledge gap in understanding how humans use proprioception to reach a specific location on a dashboard. The upcoming study in Chapter six was inspired by this problem. We will further investigate how accurately humans can reach different dashboard controls at different distances from their bodies using only proprioception.

5.2.2 Fine Approach Failure

When subjects were unable to reach the nubbins on the stencil using only proprioception, they had the the option of searching for the desired nubbin using tactile sensations. However, we discovered that subjects were unable to distinguish the tactile sensations of nubbins on a stencil (Fine approach step of the framework). On both stencils (grid and nubbin), we used two different shapes of nubbins (circle and square), and we expected these nubbins to have sufficiently distinct tactile sensations. Subjects, on the other hand, were unable to distinguish between the tactile sensations provided by the nubbins.

We also need to understand how humans distinguish between different tactile sensations. In future studies, we will investigate different tactile sensations of in-vehicle dashboard controls to learn about features that make controls easily distinguishable.

5.2.3 Perform Action Failure

We also identified that the 'span and tap' interaction mechanism for target selection on stencils performed poorly. We discovered that subjects were unable to perform the required gesture with two fingers. Especially when the desired target was located below the nubbin. We also noticed that the subjects attempted to make the desired gesture using different finger combinations; however, they still struggled to make the desired gesture. This problem has been reported by several subjects in post-experiment results.

The failure of the interaction mechanism in our study has pointed us in the right direction for future research on eyes-free selection gestures for a touchscreen. Several authors have already proposed a gesture taxonomy for touchscreen displays

[44], [74], [100]. We will investigate different gestures that are easy to use and have the potential to enable eyes-free selection for in-vehicle touchscreen while driving based on the existing taxonomies. We have already tried two touchscreen interaction gestures: ‘drag and release’ and ‘span and tap,’ but both failed on layout-agnostic stencils.

5.3 Summary

To summarise Study-I of this research. We discovered that layout-agnostic stencils failed to reduce the visual attentional demands of in-vehicle touchscreens. The extensive stencil design process and efforts we expended to make them work did not yield a positive result. As a result, we do not recommend using similar style stencils for in-vehicle touchscreens.

To identify the root causes of Study-I failure, we proposed a *In-vehicle Dashboard Interaction Framework*. We used the framework to analyse our experimental results and discovered three knowledge gaps regarding human capabilities for dashboard interaction while driving. First, we must determine how precisely humans can use proprioception to reach dashboard controls. Second, how well humans distinguish between various tactile sensations and Third, what touchscreen interaction techniques can allow for eyes-free interaction while driving?

Based on these findings, we set another objective for this thesis: to determine how accurately humans can reach dashboard controls using only proprioception. The methods for assessing proprioception abilities are covered in the following chapter.

Chapter 6

Evaluating Human Proprioceptive Capabilities

The framework proposed in Study-II of this thesis identified three knowledge gaps regarding the understanding of human-dashboard interaction in vehicles while driving. The first knowledge gap was an understanding of how humans use their proprioceptive abilities to reach dashboard controls while driving. In this regard, we have established a new goal to continue our research on our primary goal of proposing new in-vehicle touchscreen interactions to reduce visual attentional demands while driving. The goal of Study-III is to empirically characterise the accuracy of proprioceptive target acquisition for in-vehicle touchscreens while driving.

The empirical characterisation of the accuracy of in-vehicle proprioceptive target acquisition can help us understand how precisely humans can reach a specific location on the touchscreen in relation to the body's distance. Based on the findings, existing touchscreen user interfaces (in terms of size and layout) can be modified to enable eyes-free proprioceptive interaction on the touchscreen, potentially reducing visual attention demands.

6.1 Proprioception Evaluation

This section describes the objectives of this study, as well as the driving simulator, touchscreen interface, experiment design, experiment procedure, and data analysis. The Human Ethics Committee at the University of Canterbury approved this experiment (approval letter is attached in Appendix E). The subject's information sheet and consent form is also attached in (Appendix F).

The purpose of this study was to empirically characterise proprioceptive target acquisition for in-vehicle touchscreens. Under this objective, we further investigate the following research questions:

- How touchscreen to body distance affects proprioceptive target acquisition accuracy?
- Is there any difference between vertical and horizontal axis target acquisition accuracy?
- How driving a vehicle can affect the proprioceptive target acquisition accuracy?

We can infer how large targets need to be to facilitate specific accuracy levels across the distance from the body by answering the above questions. We are also interested in learning how dual-task scenarios, such as driving, affect proprioceptive target acquisition accuracy. We do not need proprioception interaction when the car is not driving because there are no safety concerns, so we can just look directly at the screen. However, we may learn something new that we can apply to our future research.

We conducted an experiment to investigate human proprioception's ability to reach in-vehicle touchscreen controls. The experiment consisted of four phases, as follows: Familiarization, Training, Proprioceptive target acquisition without driving, and Proprioceptive target acquisition with driving.

6.1.1 Driving Simulator

With a few minor changes, we used the same driving simulator from Study I of this research. The results of Study-I revealed that the steering wheel force settings were quite difficult for several subjects, particularly females. They expressed concern in the post-experiment feedback that they might not be able to control the steering wheel with one hand if they let their one hand off the steering wheel to select the target icon on the touchscreen.

As a result, in this study, we reduced the force required to steer the car. We attempted to simulate the force required on the steering wheel of a modern vehicle. We experimented with various force settings before settling on the best one. With the new settings, the majority of the subjects were able to control the car with one hand.

6.1.2 Touchscreen Interface

The touchscreen graphical user interface was designed in a Grid format (3 rows $\times$ 4 columns; a total of 12 icons were displayed), as shown in Figure 6.1. Each column on the interface was set with regard to distance from the body. The distance between the columns (from right to left, the right being the closest to the steering wheel) was as follows: 20cm, 32cm, 44cm and 56 cm.

We considered the centre of the steering wheel as the user's body distance because the steering wheel setting in a car is properly centered with the driver's seat.

The chair used in the experiment was also properly positioned at the center of the steering wheel.

The interaction metaphor we used in this experiment was a tap. A user can tap with any finger on the touchscreen to complete the target acquisition.

6.1.3 Experiment Setup

In this study, subjects completed a simulated driving task (steering a car). Periodically, a target icon was displayed at the top of the driving screen (as shown in Figure 6.1 and subjects had to select the same target on the touchscreen. Subjects were instructed to select the targets as accurately as possible.

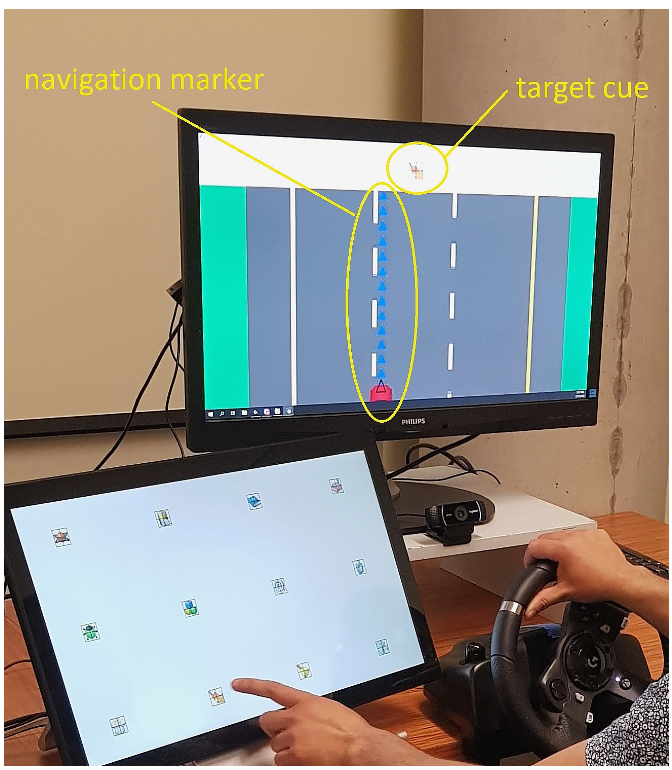


Figure 6.1: Study-III Driving Simulator and Touchscreen

The experiment was conducted in a controlled environment at a local university. The subject sat on a standard office chair. We have used the same driving simulator from Study-I. The simulated driving task involved the horizontal movement of the car on a three-lane highway; the car was running at a constant speed of 60 km/h. The initial position of the car and navigation marker was on the centre lane; however, the marker moves across all three lanes randomly after every 5 seconds. For example, it can move from right to centre or left lane, center to left or right lane, and left to center or right lane.

6.1.4 Subjects and Apparatus

Sixteen subjects were recruited from a local university (students and staff), eleven of whom were male and five of whom were female. All subjects were familiar with touchscreen interaction and had held a valid right-hand driving licence for at least one year. The subjects ranged in age from 18 to 46 years old, with an average arm span of 172.65 cm (min 153 and max 193 cm). The arm span was measured to see if there was a difference in target selection accuracy for different arm span lengths. Subjects were given a $10 cafe voucher as a token of appreciation for participating in the study.

The horizontal movement of the car was controlled by a Logitech G920 steering wheel. Touch input was collected using a Dell 21.5” capacitive touchscreen (model ST2240T) mounted on the left side of the steering wheel. A 27-inch screen was placed in front of the subject to show the target cue and driving simulation. The subjects sat in a standard office chair. For all subjects, all equipment was fixed and remained in the same position. However, at the start of the experiment, subjects were asked to adjust the position of the chair to their comfort level.

Python logging scripts automatically recorded user actions (target selection and driving accuracy data). We also recorded videos with a webcam to capture the subjects of subjects in order to analyse their gaze direction. Subjects were not permitted to look at the touchscreen during the experiment's testing phases. With video recordings, we validated this. The experimenter manually analysed video recordings.

6.1.5 Experiment Design

The experiment was to use the following within-subjects factors:

- distance from body $\in$ {*20 cm, 32 cm, 44 cm, 56 cm*}
- block $\in$ {*f1..f2, tr0..tr11, wod12..wod16, wd17..wd21*}

F1..f2 are familiarisation blocks, tr0..tr6 are training blocks, wod12..wod16 are testing blocks of proprioceptive target acquisition without-driving and wd17..wd21 are testing blocks of proprioceptive target acquisition with-driving.

The mean miss distance in pixels was used as a dependent measure (Euclidian, horizontal and vertical). Each touchscreen target had a bounding box with the centroid point (0,0) pixels. Subjects were instructed to hit the target's centroid point. The target attempt is calculated as the distance between the target's centroid point (x0,y0) pixels and the user's touch contact on the touchscreen (x1,y1) pixels. The decision was made based on the first lift-off. To assess target acquisition accuracy, we examined three types of distances: mean miss Euclidian distance, mean miss Horizontal distance, and mean miss Vertical distance.

6.1.6 Procedure

The experimenter briefed the subjects on the procedure, explaining that the task was to select the cue of targets on the touchscreen while driving. The phases of the experiment were as follows:

Familiarisation phase: the subjects were introduced to the target selection and driving control procedure. To notify the subjects that a target had appeared on the screen, a beep sound was played (on the top of the driving simulation). Subjects were required to select the same target on the touchscreen as precisely as possible. During this phase, twelve icons were displayed on the touchscreens in a grid format (3 rows *times* 4 columns), and the system randomly selected four targets (one from each column) as candidate items. The familiarisation phase consisted of two blocks of cued targets, with each subject making a total of eight selections.

Training phase: The purpose of the training was to develop subject's proprioceptive knowledge of target locations on the touchscreen to enable eyes-free selection while driving. Subjects could develop proprioceptive knowledge by repeatedly selecting the same targets, which could aid in locating targets on the touchscreen using only proprioception, eventually enabling eyes-free interaction while driving. The same procedure was used; twelve targets, four of which were candidate items, were displayed. To avoid the learning curve from the Familiarisation phase, a new set of icons was used. The training phase consisted of 12 blocks of cued targets, with each subject making a total of 48 selections while driving.

Testing-1: Proprioception target acquisition without-driving phase: The same icons and targets were used as in the training phase, except that the icons on the touchscreen were always hidden. Subjects were instructed to select the targets without looking at the touchscreen at all. Subjects were not required to drive the car; however, they were instructed to keep both hands on the steering wheel at all times, except when selecting a touchscreen target. This phase consisted of 5 blocks of cued targets, with each subject making a total of 20 selections.

Testing-2: Proprioception target acquisition with-driving phase: The same icons, targets, and procedure as in the previous phase, except this time the subjects had to drive the car. This phase consisted of 5 blocks of cued targets, with each subject making a total of 20 selections while driving.

After completing all 96 selections (8 — practice, 48 — training, 20 — testing-1, and 20 — testing2), the subject was asked to provide feedback on the experiment as well as answer several structured questions (Appendix G). Target selection accuracy and difficulty, touchscreen landmarks, driving task performance and difficulty, and selecting targets without looking at the touchscreen were among the structured questions.

6.1.7 Data Analysis

We collected experiment data from two different sources. Touchscreen interaction logs were recorded using Python scripts, and eye-gaze data was captured using a web cam. The experiment manually analysed video footage of the subjects. To analyse experimental data, we used R scripts.

Chapter 7

Results of Human Proprioceptive Capabilities

The results of human proprioceptive target acquisition capabilities to reach touchscreen controls are presented in this chapter. The chapter is divided into two parts. The first section presents statistical results, and the second section discusses those results.

7.1 Results

The following sections present the results of training, proprioceptive target acquisition without and with driving, and the subjective post-experiment response. We also presented the results of Training phase to see the results of dependent measure when visual feedback was presents on the touchscreen. The use of Greenhouse-Geisser corrections for sphericity violations (detected with Mauchley's tests) results in floating-point values for degrees of freedom in the statistical analyses.

The proprioceptive target acquisition accuracy is analysed with three distances as follows: Mean miss Euclidean distance, mean miss Horizontal distance and mean miss Vertical distance. The Euclidean distance is the distance between the target's centroid point (x0,y0) pixels and the user's touch contact on the touchscreen (x1,y1) pixels. The horizontal distance is the distance between the target's (x0) pixel and the user's (x1) pixel of touch contact. The vertical distance is the distance between the target's (y0) pixel and the user's (y1) pixel of touch contact.

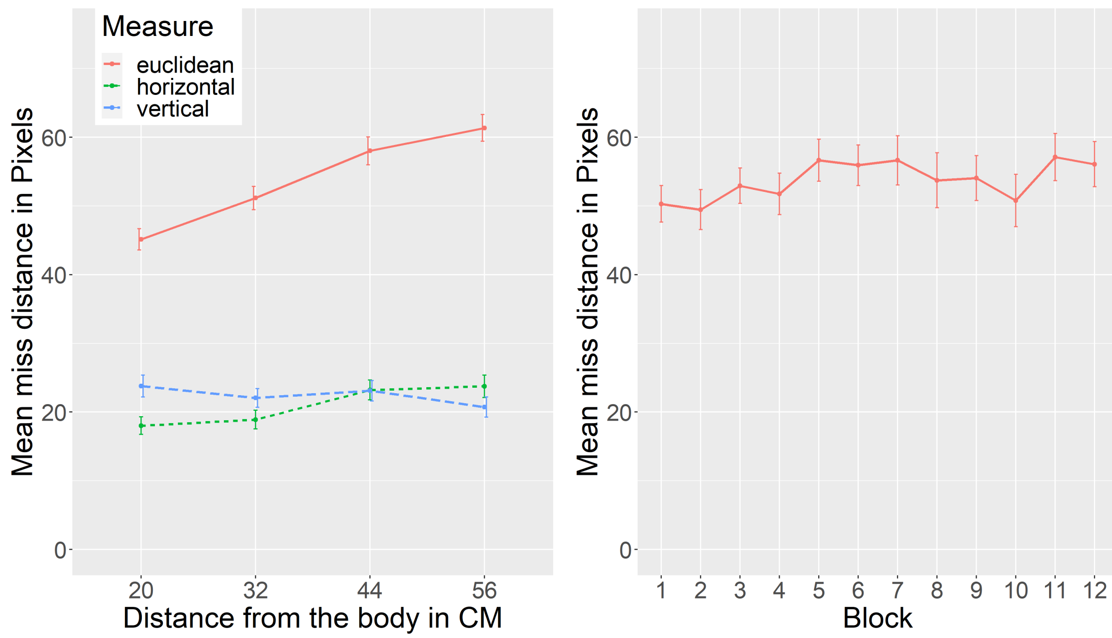
7.1.1 Training Phase

Figure 7.1a shows the mean miss euclidean, horizontal and vertical distance in pixel from the target for various distances from the body. The result shows significant effect of euclidean distance from the body ($F_{2.08,31.33} = 9.02, p = 8.6 \times 10^{-5}, \eta^2 = 0.27$), with mean distance of 45 pixels (s.d., 21) at 20 cm distance, 51 pixels (s.d., 22) at 32 cm, 58 pixels (s.d, 27) at 44 cm, and 61 pixels (s.d., 26) at 56 cm. These results show that the mean miss Euclidean distance has increased concerning distance from the body.

The results showed no significant effect of axis (horizontal and vertical distance) ($F_{1,15} = 3.26, p = 0.09, \eta^2 = 0.007$), the targets at 20 cm had high miss distance on vertical axis as compared to the other targets. Figure 7.1b shows the results of mean miss distance by block, no significant effect of block was observed ($F_{11,165} = 1.02, p = 0.43, \eta^2 = 0.04$), with miss distance remaining consistent across blocks.

7.1.2 Testing-1: Proprioceptive target acquisition without driving

Figure 7.2a shows the mean miss euclidean, horizontal and vertical distance of pixel from the target for various distances from the body. The results show a significant effect of distance from the body ($F_{2.82,42.37} = 5.53, p = 0.002, \eta^2 = 0.21$), with mean miss distance of 97 pixels (s.d., 73) at 20 cm distance, 132 pixels (s.d., 70)



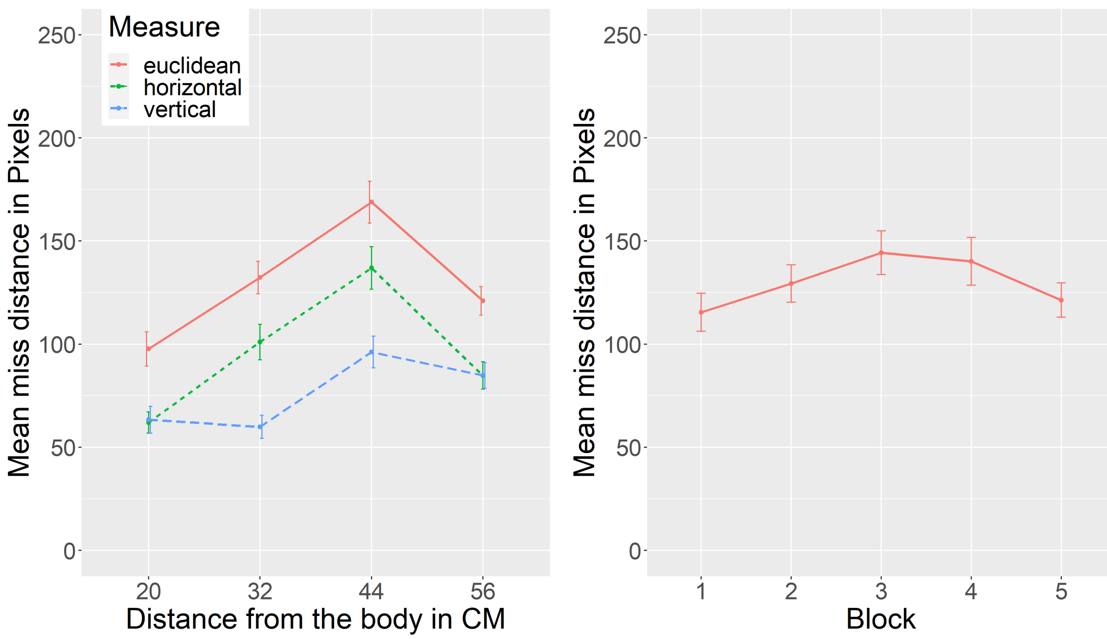
(a) Mean miss distance in pixels by Distance (b) Mean miss distance in pixels by Block

Figure 7.1: Showing mean miss distance of training phase. Error bars represent standard errors.

at 32 cm, 168 pixels (s.d, 90) at 44 cm, and 120 pixels (s.d., 61) at 56 cm. The targets in the middle of the screen had a high miss distance as compared to the nearest and furthest targets.

The results also showed a significant effect of axis (horizontal and vertical distance) ($F_{1,15} = 4.39, p = 0.05, \eta^2 = 0.05$), the targets at 20 cm and 56 cm had similar miss distances, however the targets in the middle of the touchscreen had a high miss distance on the horizontal axis, meaning that the subject's proprioceptive horizontal arm movement (right/left movement) in the middle of the touchscreen was less accurate than their proprioceptive vertical arm movement (up/down movement).

Figure 7.2b shows the mean miss distance by blocks. The result shows no significant effect of block ($F_{3,45} = 1.65, p = 0.19, \eta^2 = 0.05$), with miss distance remaining relatively consistent across blocks.



(a) Mean miss distance in pixels by Distance (b) Mean miss distance in pixels by Block

Figure 7.2: Showing proprioceptive acquisition miss distance without driving. Error bars represent standard errors.

7.1.3 Testing-2: Proprioceptive target acquisition with driving

Figure 7.3a shows the mean miss euclidean, horizontal, and vertical distance of pixels from the target for various distances from the body. The results show a significant effect of distance from the body ($F_{2.40,36.13} = 7.02, p = 0.0005, \eta^2 = 0.27$) with a mean miss distance of 100 pixels (s.d., 50) at 20 cm distance, 167 pixels (s.d., 81) for 32 cm, 185 pixels (s.d, 86) for 44 cm, and 142 pixels (s.d., 81) for 56 cm. The targets in the middle of the touchscreen had a high miss distance, as compared to the nearest and furthest targets.

The results also showed a significant effect of axis ($F_{1,15} = 60.21, p = 1.25 \times 10^{-6}, \eta^2 = 0.25$), the targets in the middle of the touchscreen had a significant high miss distance on the horizontal axis. These results show that the subjects had better proprioception arm movement on the vertical axis (up/down movement) than horizontal movement (right/left movement).

Figure 7.3b shows the mean miss distance by blocks. The results show no significant effect of block ($F_{3,45} = 0.90, p = 0.44, \eta^2 = 0.02$), with consistent miss distance across blocks.

(a) Mean miss distance in pixels by Distance

(b) Mean miss distance in pixels by Block

Figure 7.3: Showing proprioceptive target acquisition miss distance with driving. Error bars represent standard errors.

7.1.4 Comparative target acquisition accuracy

Figure 7.4 shows the comparison of proprioceptive target acquisition miss distance with and without driving. The results show a significant difference of task type ($F_{1,15} = 7.99, p = 0.01, \eta^2 = 0.02$), with a mean miss distance of 97 pixels (s.d., 73) without driving and 100 pixels (s.d, 50) with driving at 20 cm distance. At 32 cm distance, 132 pixels (s.d., 70) without driving and 167 pixels (s.d., 81) with driving. At 44 cm, 168 pixels (s.d, 90) without driving and 185 pixels (s.d, 86). At 56 cm, 120 pixels (s.d., 61) without driving and 142 pixels (s.d., 81) with driving. Proprioceptive miss distance without driving was low as compared to driving.

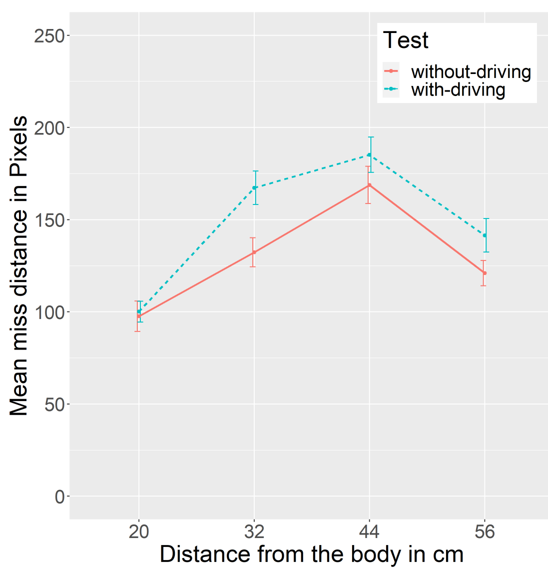


Figure 7.4: Showing comparative proprioceptive target acquisition miss distance. Error bars represent standard errors.

7.1.5 Subjective Responses

When asked, “Which target on the touchscreen was easy to select?", the majority of subjects said the targets near the corner were easy to select, while the targets in the middle of the screen were the most difficult to select. Some subjects also commented that the screen was too large to accurately predict the approximate location of targets without looking.

When asked, “How did you memorise the touchscreen targets?" based on their position, colours, shape, or any other clue" Half of the subjects said the touchscreen’s landmarks (bezels) helped them remember, and some said the position of icons, such as “telephone icon was top corner” and “Facebook icon was in the middle of the screen," helped them remember.

When asked about their confidence in target selection accuracy, the majority of subjects stated, “we anticipated that we were selecting accurately; however, it was difficult to tell when you are not allowed to look at the touchscreen."

When asked how difficult the driving task was, most of the subjects said it was difficult because they had to steer the car more frequently than real driving. Subjects also reported that selecting targets while driving was mentally demanding, and that they felt they were losing control of the driving task when they looked at the touchscreen during the training phase.

7.2 Discussion

We evaluated the ability of human proprioceptive target acquisition to reach touchscreen controls while seated (with and without driving). We discovered how far (miss distance) a user could reach on the touchscreen in relation to the body’s distance. The miss distance was low for targets close to the body at a distance of 20 cm. The targets furthest away from the body, at 56 cm, had an average miss distance, while the targets in the middle of the touchscreen, at 32 and 44 cm, had a high miss distance.

It is worth noting that the targets furthest away from the body had a lower miss distance than the targets in the centre of the touchscreen. The proprioception arm lock is one of two possible explanations for this result. Most of the subjects had to stretch their arms at full length to make contact with the targets that were 56 cm away from the body. Extending the arm to full length aided subjects in selecting the target with minimal miss distance because they were certain that the target was at this arm length. This scenario, however, is less effective for subjects with a large arm span (> 185 cm). We expected them to extend their arm fully, then move their arm slightly inwards to the touchscreen to make the final adjustment. The second reason could be the touchscreen landmarks (bezels); the bezels may have aided in the selection of the target. Despite the fact that they were not looking at the touchscreen while selecting the targets, landmarks may have aided them due to their peripheral vision.

Based on miss distance results (means and standard deviation) for the targets' distance from the body. We can now anticipate how large the targets on the touchscreen will need to be in order to enable eyes-free proprioceptive target acquisition while driving. To achieve a certain level of proprioceptive target accuracy, we calculated the size of touchscreen controls based on miss distance results. We presented the size of touchscreen controls in centimetres to be generalizable regardless of touchscreen resolution and size.

7.2.1 Empirical characterisation of accuracy for proprioceptive target acquisition for in-vehicle touchscreens

Table 7.1 shows the size in cm of touchscreen controls to enable eyes-free proprioceptive target acquisition while driving. Based on our experimental data, we

Table 7.1: Proposed size of touchscreen controls to enable eyes-free proprioceptive target acquisition while driving

	DIAMETER			HEIGHT			WIDTH		
	Accuracy (percentile)								
distance	**0.85**	**0.90**	**0.95**	**0.85**	**0.90**	**0.95**	**0.85**	**0.90**	**0.95**
20	3.7	4.1	4.4	2.2	2.6	2.9	2.8	3.3	3.9
32	6.2	6.4	7.1	3.2	3.6	3.9	5.4	6.1	7.0
44	6.4	7.2	8.1	3.3	3.4	3.6	7.1	7.5	8.4
56	5.7	6.1	7.3	3.8	4.4	4.7	4.3	4.6	5.4

have proposed different sizes of controls to achieve a certain level of accuracy. For example, to achieve 85% accuracy, the target at a distance of 20 cm needs to be 3.71 cm in diameter, 4.07 cm for 90% accuracy, and 4.35 cm for 95% accuracy.

We have also learned from the results that humans have different horizontal (right/left movement) and vertical proprioceptive (up/down movement) target miss distances. Subjects had low miss distance on the vertical axis as compared to the horizontal. Therefore, it is not necessary to design touchscreen controls in circles and square shapes only. Touchscreen controls could have different widths and heights to optimise the layout of the interface. Proposed heights of controls to achieve a certain level of accuracy are shown in Table 7.1. For example, to achieve 85% accuracy, the target at a distance of 20 cm needs to be 2.17 cm tall, 2.57 cm for 90% accuracy, and 2.94 cm for 95% accuracy. Similarly, the proposed width of controls to achieve a certain level of accuracy is also shown in Table 7.1.

The proposed sizes can be used to modify existing touchscreen control sizes to enable eyes-free proprioceptive target acquisition while driving. We could reduce the visual attentional demands required to use the touchscreen and improve touchscreen safety by taking this approach. With the size of the touchscreen controls modified, touchscreen controls can be acquired solely through proprioception, without taking one's gaze away from the road. Furthermore, because this approach does not require any additional components to be installed on the touchscreen, it could be a quick solution to reduce the visual attentional demands of modern in-vehicle touchscreens.

It was also discovered that, with the proposed sizes, some controls on the touchscreen must be enormous in terms of distance from the body. For example, to achieve 85% accuracy at a distance of 44 cm from the body, the control must be 6.4 cm in diameter. This is a large size for a single control, and it will take enormous space on a touchscreen. One application for such large controls is to answer incoming calls, track changing controls on a media player, or change radio stations. Placing two large buttons side by side in the centre of the touchscreen to answer phone calls could be an efficient use of space. The second option for improving the centre portion of the touchscreen is to include some tactile guides in the centre of the touchscreen. Tactile guides can help the user acquire targets without looking by providing tactile sensations. However, more research is needed in this area. The limitations of this study will be addressed in our upcoming work on in-vehicle touchscreens.

Furthermore, there was a significant difference between driving and non-driving proprioceptive target acquisition; proprioceptive mean miss distance increased while driving. There are two possible explanations for this outcome. First, the mental demands of driving a car have impacted proprioception abilities. The order of the experiment could be the second reason. In the final phase of the experiment, subjects were tested for proprioceptive target acquisition while driving. Fatigue could have had an impact on proprioceptive performance. Despite the fact that the experiment lasted only 20 minutes, the subjects were not likely to be exhausted during the final phase. As a result, we believe that a decrease in proprioceptive target acquisition accuracy is more likely due to the mental demands of driving a car.

7.3 Summary

To summarise the Study-III of this research. The framework proposed in Chapter 5 identified three knowledge gaps related to human capabilities to interact with dashboard controls while driving. One of the gaps was a lack of understanding of human proprioceptive capabilities for reaching dashboard controls. We conducted an experimental study to evaluate humans' proprioceptive abilities and discovered how accurately humans could reach a specific location on a touchscreen using proprioception based on distance from the body. We empirically characterise accuracy for proprioceptive target acquisition for in-vehicle touchscreens based on the results. We proposed touchscreen sizes that would allow for eyes-free proprioceptive target acquisition while driving. Existing touchscreen control sizes can be modified to reduce visual attentional demands and improve touchscreen safety using the recommended size.

Chapter 8

General Discussion, Future Work and Conclusions

Touchscreens in vehicles provide access to a variety of vehicle functions. Touchscreens, on the other hand, are attention demanding due to a lack of tactile feedback, and all touchscreen controls have the same tactile sensation. The absence of these features raises visual attentional demands and degrades driving performance, raising safety concerns. In terms of in-vehicle touchscreen safety, this thesis motivates the development of new in-vehicle touchscreen interaction methods while driving.

8.1 Progress on Research Objectives

The primary goal of this thesis was to propose new touchscreen interaction methods that would reduce visual attentional demands while improving driving performance. The primary goal, as stated in Chapter 1, was expanded into three research objectives:

- **Study-I: Examine the design and use of layout-agnostic stencil**

overlays for in-vehicle touchscreen.

- **Study-II: A framework to explore the failure of layout-agnostic stencils.**
- **Study-III: To empirically characterise proprioceptive target acquisition accuracy for in-vehicle touchscreens while driving**

The first objective of this study was presented in Chapters 3 and 4 of this thesis. The methods for designing and evaluating layout-agnostic stencil overlays for in-vehicle touchscreens were presented in Chapter 3. Design objectives, the stencil design process, and experimental methods were all discussed. The results of layout-agnostic stencils were presented in Chapter 4. Based on those findings, we discovered that the layout-agnostic stencils failed to reduce attentional demands and actually worsened driving performance. This learning outcome cautioned other vehicle researchers not to use layout-agnostic stencils like the one we used in this study.

The failure of Study-I inspired us to learn more about how humans interact with dashboard controls while driving. In this regard, we establish the second goal of this research, which is presented in Chapter 5 of this thesis. A “In-vehicle dashboard controls interaction framework" was presented in Chapter 5. The framework provides a better understanding of how humans interact with dashboard controls in vehicles while driving. We also used the framework to evaluate the Study-I results, and we evaluated three knowledge gaps that indicate a lack of understanding of humans interacting with dashboard controls while driving.

We continued our research to improve in-vehicle touchscreens based on the identified knowledge gaps. In this regard, we established the third goal of this study. Chapter 6 presented the methods used to evaluate human proprioceptive abilities to reach a specific location on a touchscreen, and Chapter 7 presented the results of the evaluations.

In summary, the work presented in this thesis addresses all three objectives of this research, adding new insights to the field of in-vehicle touchscreen interaction research. It provides a better understanding of how to use stencil overlays for in-vehicle touchscreens. It provides a better understanding of human-dashboard interaction with the framework, and it concludes with the empirical characterisation of accuracy for proprioceptive target acquisition in order to enable eyes-free interaction while driving.

8.2 Generalisation of Results and Future Work

This thesis included theoretical knowledge of human factors as well as experiments on various in-vehicle touchscreen topics. The knowledge gained from these experiments and theoretical concepts can be applied to large-scale in-vehicle studies. The subsections that follow go over the results obtained from layout-agnostic stencils, the framework, and human proprioceptive abilities.

8.2.1 Layout-agnostic stencil overlays

The main objective of developing layout-agnostic stencils was to overcome the limitations of layout-specific stencils (limited to use only with one underlying user interface). The study was motivated by previous studies' successes with layout-specific stencils. Our layout agnostic stencils failed to achieve their goals, increasing visual attention and distraction rather than decreasing it. However, when compared to the Normal touchscreen, the Nubbin stencil was rated as the best target selection approach with the least visual demand, indicating some positive evidence of intended success. Similar findings were reported in several prior stencil-based studies, in which subjects favoured stencil overlays over standard touchscreens [13], [15], [47], [61], [76]. The lesson learned from this study is that the layout-agnostic stencil designs we used in this study will not reduce visual attentional demands and improve driving performance. As a result, we do not recommend replicating designs similar to those used in our study.

We also discovered several interaction issues with our stencil after evaluating it using the proposed framework, which revealed that our stencil failed at both the Coarse (proprioception) and Fine approaches (tactile sensations). Based on our experience and the findings of Study-I, one promising future direction for developing layout-agnostic stencil overlays that could reduce the visual attentional demands of touchscreens is to improve physical augmentations (e.g., nubbins). The nubbins used in our study were small and did not produce distinct tactile sensations. Those nubbins could be improved so that they could be used with proprioception and tactile sensations, as we intended in our study. Making the nubbins bigger may allow proprioception (coarse approach) to reach them. For example, we are likely to reach steering wheel, gear lever, and possibly several other dashboard controls solely through proprioception. Experimenting with nubbin size could yield promising results. Another way to reach those nubbins is to use different shapes and textures that provide rich distinct tactile sensations, allowing the user to easily differentiate between different nubbins and guide their finger to underlying touchscreen controls. Making these two suggested changes to layout-agnostic stencils could yield promising results in terms of lowering visual attentional demands. We also considered conducting another study based on these recommendations; however, after the failure of Study-I, we were hesitant to take another risk.

8.2.2 The in-vehicle dashboard interaction framework

To the best of our knowledge, the framework proposed in Chapter 5 is the first and only framework in the vehicle research domain. The framework provides a low-level understanding of human factors related to vehicle dashboard controls while driving. This framework has a number of applications in the field of vehicle dashboard research in general. First, the framework's design and presentation can be used to create new in-vehicle dashboard interaction techniques because interested researchers and vehicle manufacturers can now better understand how humans process and execute information while interacting with dashboard controls. Second, it can be used to evaluate existing dashboard interaction studies. Researchers could evaluate their studies in relation to the framework's phases and interaction steps, as we did in Chapter 5. Evaluating existing studies using the framework could enrich existing knowledge, explore new gaps, and point to future directions.

We also used the framework to evaluate the results of Study-I and identified three knowledge gaps, the first of which we evaluated in Study-III of this research. However, two knowledge gaps remain unresolved, and these are recommended for future work. First, it was discovered that there is a lack of understanding about how accurately humans can differentiate between different tactile sensations. Addressing this knowledge gap could lead to a better understanding of tactile sensations for various dashboard controls and the development of new interaction methods (e.g., different layout-agnostic stencils). Second, a lack of understanding of touchscreen interaction gestures for vehicle use was discovered. We evaluated two new touchscreen interaction gestures ('drag and release' and 'span and tap') and found them both to be ineffective (Perform Action step of the framework). As a result, we recommend conducting research on the evaluation of various touchscreen interaction gestures that are simple to use and may enable eyes-free interaction while driving. Researchers and vehicle manufacturers who are interested in these future directions can conduct studies to generalise human tactile sensation capabilities and taxonomy of touchscreen gestures that are best suited for in-vehicle touchscreen use. With the fast growth of in-vehicle touchscreens in modern vehicles, it is critical to address these issues.

8.2.3 Human proprioceptive capabilities

We empirically characterise proprioceptive target acquisition accuracy for in-vehicle touchscreens. We presented different sizes of touchscreen controls based on the characterisation, which can be used to modify existing touchscreen controls or develop new with recommended sizes to enable eyes-free proprioceptive target acquisition while driving.

The characteriszation of proprioceptive target acquisition capabilities suggests several new future directions, which are as follows. To begin, how do the proposed touchscreen control sizes work with different touchscreen sizes and orientations? Touchscreen sizes and orientations vary by vehicle manufacturer, ranging from 7" to 17". We proposed sizes in centimetres to generalise for different touchscreens; however, we recommend testing the proposed sizes on different touchscreens to see how those sizes fit on the screen and how the touchscreen interface layout can be designed. Second, some of the proposed control sizes were enormous and would most likely take up a lot of space on a touchscreen. As a result, more research on utilising those large controls and what touchscreen functions could be used to facilitate such large controls is required. Third, the first two recommendations should be evaluated for external validity in a real-world driving scenario.

Furthermore, when comparing different display conditions, the mean path deviation measure has failed to produce significant results. As a result, we evaluated driving performance using two new performance measures: maximum path deviation and variance of path deviation across time. Both new measures were successful in demonstrating statistically significant differences in driving performance. As a result, we recommend using these measures in future studies because they are more sensitive to evaluating driving performance.

8.3 Conclusions

Touchscreens have become an absolutely essential part of modern life, with billions of devices employing them. Touchscreens are also widely used in vehicles, particularly automotive. However, in-vehicle touchscreens are attention demanding, which raises safety concerns. As a result, we sought to reduce visual attentional demands. First, we created and evaluated layout-agnostic stencils, which failed to reduce visual attentional demands and worsen driving performance. Second, the failure of the layout-agnostic stencil inspired us to continue our work on the in-vehicle touchscreen. We then proposed an in-vehicle dashboard controls interaction framework, evaluated the layout-agnostic stencil results, and identified three knowledge gaps. Third, we conducted another study on the first knowledge gap to better understand human proprioceptive abilities in order to reach dashboard controls.

This thesis has made three research contributions to the in-vehicle touchscreens domain, presented as follows:

1. **Better understanding of stencil overlays for in-vehicle touchscreens.** Previous research has shown that layout-specific stencils can reduce the visual demands of in-vehicle touchscreens. However, as previously mentioned, those stencils had limitations. We designed and evaluated layout-agnostic

stencils in this regard, but they failed. We have learned from our experiences that the layout-agnostic stencil designs we used in our study are unlikely to work, and we do not recommend using them.

2. **In-vehicle dashboard control interaction framework.** The proposed framework provides a better understanding of how drivers interact with dashboard controls in vehicles. The proposed framework could help with a variety of in-vehicle touchscreen research studies. First, using in-vehicle controls to better understand low-level human activities while driving could be beneficial. Second, while driving, it could be used to assess in-vehicle dashboard interaction. Third, it may aid car manufacturers and researchers in the development of new systems that are less visually demanding and distracting.

3. **A characterisation of accuracy of proprioceptive target acquisition for in-vehicle touchscreens.** We can determine how accurately humans can reach a specific location on the touchscreen from various distances based on the characterisation. To enable eyes-free proprioceptive target acquisition while driving, we proposed the size (in cm) of touchscreen controls to achieve a certain level of accuracy for various dashboard to body distances. Existing touchscreen user interfaces can be modified to enable eyes-free proprioceptive interaction on the touchscreen based on our recommendations.

In conclusion, this thesis has presented novel knowledge on understanding in-vehicle touchscreens and human factors. This thesis also provided several future directions for future research on the in-vehicle touchscreen to reduce visual attentional demands and make them safer to use while driving.

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Appendix A

Study-I: Human Ethics Committee Approval Letter

UC UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

HUMAN ETHICS COMMITTEE

Secretary, Rebecca Robinson
Telephone: +64 03 369 4588, Extn 94588
Email: human-ethics@canterbury.ac.nz

Ref: HEC 2018/28/LR-PS

25 June 2018

Sarmad Soomro
Computer Science and Software Engineering
UNIVERSITY OF CANTERBURY

Dear Sarmad

Thank you for submitting your low risk application to the Human Ethics Committee for the research proposal titled "Stencil Overlays for In-Vehicle Touchscreen Interaction".

I am pleased to advise that this application has been reviewed and approved.

Please note that this approval is subject to the incorporation of the amendments you have provided in your email of 20th June 2018.

With best wishes for your project.

Yours sincerely

pp. R. Robinson

Professor Jane Maidment
Chair, Human Ethics Committee

Appendix B

Study-I: Experiment Information Sheet and Consent Form

CSSE Department
Telephone: 6624
Email: sarmad.soomro@pg.canterbury.ac.nz

Stencil overlays for in-vehicle touchscreen interaction

Modern vehicles commonly use touch displays and touch sensitive surfaces as their main interaction method for users to operate secondary functions of the vehicle, such as changing the media player, navigation, air conditioning etc. Traditionally this was done with physical switches / buttons, which provide a haptic response to the user and allows a user to reach out and feel for the action they want to perform without diverting significant attention time from driving. However, with touch displays the user has no haptic feedback through the sense of touch and is required to divert more of their attention into performing this secondary task. This has a significant impact as the lack of tactile feedback requires more attentional demands which leads to safety concern, as drivers are likely to spend more time on interacting and using touchscreen and end up in an accident. This project seeks to use stencils overlays on touch displays to determine if a haptic response can be felt which will reduce attentional demands.

If you choose to take part in this study, your involvement in this project will be:

Practice (Approx. 5 min): Introduction to experimental method, including layout of touch screen and steering wheel controls.

Training (Approx. 30 min): Completion of simulated steering task, and queued target selections on the touchscreen.

Testing (Approx. 5 min): Completion of simulated steering task, and queued target selections on the touchscreen.

Debrief (5 min): Comments on the interactive experiences.

Participation is voluntary and you have the right to withdraw at any stage without penalty. You may ask for your raw data to be returned to you or destroyed at any point. If you withdraw, I will remove information relating to you. However, once analysis of raw data starts on 15/02/2018 it will become increasingly difficult to remove the influence of your data on the results.

The results of the project may be published, but you may be assured of the complete confidentiality of data gathered in this investigation: your identity will not be made public without your prior consent. To ensure anonymity and confidentiality, Names will not be recorded, an anonymous identifier will be used. Data will be password protected on a UC account, only accessible to the research team.

Please indicate to the researcher on the consent form if you would like to receive a copy of the summary of results of the project.

The project is being carried out as a part of PhD research carried by *Sarmad Soomro* under the supervision of *Andy Cockburn*, who can be contacted at andy@cosc.canterbury.ac.nz . They will be pleased to discuss any concerns you may have about participation in the project.

This project has been reviewed and approved by the University of Canterbury Human Ethics Committee, and participants should address any complaints to The Chair, Human Ethics Committee, University of Canterbury, Private Bag 4800, Christchurch (human-ethics@canterbury.ac.nz).

If you agree to participate in the study, you are asked to complete the consent form and return it to the experiment coordinator

Sarmad Soomro

CSSE Department
Telephone: 6624
Email: sarmad.soomro@pg.canterbury.ac.nz

Stencil overlays for in-vehicle touchscreen interaction

- ☐ I have been given a full explanation of this project and have had the opportunity to ask questions.
- ☐ I understand what is required of me if I agree to take part in the research.
- ☐ I understand that participation is voluntary and I may withdraw at any time without penalty.
- ☐ Withdrawal of participation will also include the withdrawal of any information I have provided should this remain practically achievable.
- ☐ I understand that any information or opinions I provide will be kept confidential to the researcher and that any published or reported results will not identify the participants.
- ☐ I understand that all data collected for the study will be kept in locked and secure facilities and/or in password protected electronic form and will be destroyed after 10 years.
- ☐ I understand the risks associated with taking part and how they will be managed.
- ☐ I understand that I can contact the researcher Sarmad Soomro (sarmad.soomro@pg.canterbury.ac.nz) or supervisor Andy Cockburn (andy@cosc.canterbury.ac.nz) for further information. If I have any complaints, I can contact the Chair of the University of Canterbury Human Ethics Committee, Private Bag 4800, Christchurch (human-ethics@canterbury.ac.nz)
- ☐ I would like a summary of the results of the project.
- ☐ By signing below, I agree to participate in this research project.

Name: ______________________________________ Signed: _______________________ Dated: ____________

Email address (*for report of findings, if applicable*):____

Appendix C

Study-I: NASA TLX Worksheet

NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

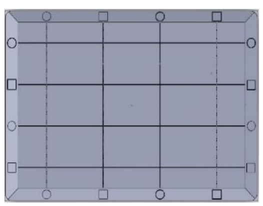
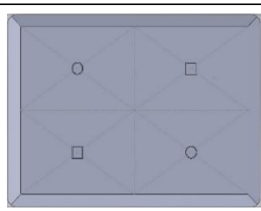
Appendix D

Study-I: Display Preferences Worksheet

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Stencil overlays for in-vehicle touchscreen interaction

Please rate the three interfaces from 1(best) to 3(worst) for all the questions in each column.

Display		Mental Demand	Physical Demand	Temporal Demand	Item Selection Performance	Effort	Frustration	Visual Attention Demand	Driving Quality	Overall Preferred
Normal										
Grid										
Nubbin										

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CHRISTCHURCH NEW ZEALAND

Any final comments on any of the interfaces?

Normal:

Grid:

Nubbin:

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CHRISTCHURCH NEW ZEALAND

Overall:

THANK YOU FOR PARTICIPATING IN THIS STUDY

Appendix E

Study-III: Human Ethics Committee Approval Letter

UC UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

HUMAN ETHICS COMMITTEE

Secretary, Rebecca Robinson
Telephone: +64 03 369 4588, Extn 94588
Email: human-ethics@canterbury.ac.nz

Ref: HEC 2020/52/LR-PS

25 September 2020

Sarmad Soomro
Computer Science and Software Engineering
UNIVERSITY OF CANTERBURY

Dear Sarmad

Thank you for submitting your low risk application to the Human Ethics Committee for the research proposal titled "Evaluating Human Capabilities of Using Proprioception to Reach Various In-Vehicle Dashboard Controls".

I am pleased to advise that this application has been reviewed and approved.

Please note that this approval is subject to the incorporation of the amendments you have provided in your email of 21st September 2020, **and the following:**

- *Please make the following changes to the Information Sheet: correct "mechanisuam", change "a reward" to "thanks" or similar, remove "...without your prior consent".*

With best wishes for your project.

Yours sincerely

Dr Dean Sutherland
Chair, Human Ethics Committee

Appendix F

Study-III: Experiment Information Sheet and Consent Form

CSSE Department
Telephone: +64 3 369 3999 Ext.6624
Email: sarmad.soomro@pg.canterbury.ac.nz
HEC Ref: HEC 2020/52/LP-PS

Evaluating Human capabilities of using proprioception to reach in-vehicle dashboard controls

I am Sarmad, a Ph.D. researcher at the Department of Computer Science and Software Engineering at the University of Canterbury, New Zealand. My research interest is working with touchscreens, particularly in-vehicle touchscreens. Modern vehicles commonly use touch displays and touch-sensitive surfaces as their main interaction method for users to operate secondary functions of the vehicle, such as changing the media player, navigation, air conditioning, etc. However, touchscreens are attention-demanding. This has a significant impact as the less attention the user pays to the road, the more likely they are to end up in an accident. This project seeks to evaluate the accuracy of muscle memory to select targets on a touchscreen at different distances from the body. The result of this project will indicate how large do the targets need to be on a touchscreen to facilitate specific levels of selection accuracy across the distance from the body using muscle memory.

You have been approached to take part in this study because you have booked a time slot to participate in the study. I have located your contact details through your response to the doodle.

If you choose to take part in this study, it will take approximately 35 minutes of your time. In this study, you will repeatedly be selecting targets on the touchscreen along with steering the car using a steering wheel. Your involvement in this project will be:

Brief (Approx. 5 min): Introduction to experimental methods, signing the consent form, and demographic information.

Familiarization (Approx. 5 min): Introduction to interaction mechanism of target selection and steering wheel controls.

Training (Approx. 15 min): Completion of simulated steering task and queued target selections on the touchscreen.

Testing (Approx. 10 min): Completion of simulated steering task and queued target selections on the touchscreen.

Debrief (5 min): Comments on interactive experiences.

The target selection and steering task data will be recorded through software logs, and a video will be recorded to analyze eye-gaze data. Analyzing how much time you spent on looking at the touchscreen.

Participation is voluntary, and you have the right to withdraw at any stage without penalty. You may ask for your raw data to be returned to you or destroyed at any point. If you withdraw, I will remove the information relating to you. However, once the analysis of raw data starts on 30/10/2020, it will become increasingly difficult to remove the influence of your data on the results.

A $10 café voucher will be given as a token of appreciation for participating in the study. If you wish to withdraw from the study at any time during the simulated task, you will still be given a café voucher.

The results of the project may be published, but you may be assured of the complete confidentiality of data gathered in this investigation: your identity will not be made public. To ensure anonymity and confidentiality, names will not be recorded and an anonymous identifier will be used. Data will be password protected on a UC account, only accessible to the research team.

Please indicate to the researcher on the consent form if you would like to receive a copy of the summary of the results of the project.

The project is being carried out as a part of PhD research carried by *Sarmad Soomro* under the supervision of *Andy Cockburn*, who can be contacted at andy@cosc.canterbury.ac.nz . They will be pleased to discuss any concerns you may have about participation in the project.

This project has been reviewed and approved by the University of Canterbury Human Ethics Committee, and participants should address any complaints to The Chair, Human Ethics Committee, University of Canterbury, Private Bag 4800, Christchurch (human-ethics@canterbury.ac.nz).

If you agree to participate in the study, you are asked to complete the consent form and return it to the experiment coordinator

Sarmad Soomro

CSSE Department
Telephone: 6624
Email: sarmad.soomro@pg.canterbury.ac.nz

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Evaluating the Human capabilities of using proprioception to reach in-vehicle dashboard controls

Name: ____________________________________ Age: ____________________________________

Gender:___________________________________ Driving Experience (year):____________________

Arm Span: _________________________________

- ☐ I have been given a full explanation of this project and have had the opportunity to ask questions.
- ☐ I understand what is required of me if I agree to take part in the research.
- ☐ I understand that participation is voluntary and I may withdraw at any time without penalty.
- ☐ Withdrawal of participation will also include the withdrawal of any information I have provided should this remain practically achievable.
- ☐ I understand that any information or opinions I provide will be kept confidential to the researcher and that any published or reported results will not identify the participants.
- ☐ I understand that all data collected for the study will be kept in locked and secure facilities and/or in password protected electronic form and will be destroyed after 10 years.
- ☐ I understand the risks associated with taking part and how they will be managed.
- ☐ I understand that I can contact the researcher Sarmad Soomro (sarmad.soomro@pg.canterbury.ac.nz) or supervisor Andy Cockburn (andy@cosc.canterbury.ac.nz) for further information. If I have any complaints, I can contact the Chair of the University of Canterbury Human Ethics Committee, Private Bag 4800, Christchurch (human-ethics@canterbury.ac.nz)
- ☐ I would like a summary of the results of the project.
- ☐ By signing below, I agree to participate in this research project.

Signed: ______________________ Dated: ____________

Email address (*for report of findings, if applicable*):____

Appendix G

Study-III: Post Experiment Questions

Participant Id: _________________

How difficult was the target selection?
Were the targets easy to find on the touchscreen? In terms of their visibility, shaped and colors.
Which target was the most easy to select?
How did you memorise the location of targets on the touchscreen? such as position, colors, shape or any other clues?
Was it convenient for you to reach the furthest target (away from the body)?
How confident you were selecting the targets when you were not allowed to look at the touchscreen?
How difficult was the driving task?
Was target selection more difficult with driving or was it same as without driving?
Was driving task was physical demanding?
Was the seating position comfortable for you?
Would you like provide any other feedback?