Active-Proprioceptive-Vibrotactile and Passive-Vibrotactile Haptics for Navigation

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Abstract

Navigation is a complex activity and an enabling skill that humans take for granted. It is vital for humans as it fosters spatial awareness, enables exploration, facilitates efficient travel, ensures safety, supports daily activities, promotes cognitive development, and provides a sense of independence. Humans have created tools for diverse activities, including navigation. Usually, these tools for navigation are vision-based, but for situations where visual channels are obstructed, unavailable, or are to be complemented for immersion or multi-tasking, touch-based tools exist. These touch-based tools or devices are called haptic displays.

Many different types of haptic displays are employed by a range of fields from telesurgery to education and navigation. In the context of navigation, certain classes of haptic displays are more popular than others, for example, passive multi-element vibrotactile haptic displays, such as haptic belts. However, certain other classes of haptic displays, such as active proprioceptive vibrotactile and passive single-element vibrotactile, may be better suited for certain practical situations and may prove to be more effective and intuitive for navigational tasks than a popular option, such as a haptic belt. However, these other classes have not been evaluated and cross-compared in the context of navigation. This research project aims to contribute towards the understanding and, consequently, the improvement of designs and user experience of navigational haptic displays by thoroughly evaluating and cross-comparing the effectiveness and intuitiveness of three classes of haptic display (passive single-element vibrotactile; passive multi-element vibrotactile; and various active proprioceptive vibrotactile) for navigation. Evaluation and cross-comparisons take into account quantitative measures, for example, accuracy, response time, number of repeats taken, experienced mental workload, and perceived usability, as well as qualitative feedback collected through informal interviews during the testing of the prototypes.

Results show that the passive single-element vibrotactile and active proprioceptive vibrotactile classes can be used as effective and intuitive navigational displays. Furthermore, results shed light on the multifaceted nature of haptic displays and their impact on user performance, preferences, and experiences. Quantitative findings related to performance combined with qualitative findings emphasise that one size does not fit all, and a tailored approach is necessary to address the varying needs and preferences of users.

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Chapter 1
Introduction

With your eyes closed can you point your thumb up, then down, then to the left, and finally, to the right? How could you do that without any input from the five basic senses: sight, hearing, smell, taste, and touch (there was no contact involved)? They are internal senses at play that we rely on for many activities; for example, when we are eating, we don't have to see and think about where the spoon full of food is heading, we can navigate a spoon from the plate to mouth with our eyes closed. Or, as another example, from a young age, I started playing video games with joysticks and, after some practice, was able to play without having to look at them, as I was aware of where my thumbs and fingers were on them. One of the questions this research tries to answer, in simple terms, is: can we use these internal senses of the body to communicate navigational information?

To provide a comprehensive understanding of the research project, this chapter begins by introducing key terminologies and concepts relevant to the study. The first section presents an overview of navigation and haptic displays, and, based on research gaps, focuses on the specific haptic displays of interest, their evaluation, and the need for cross-comparisons. Building upon this foundation, the second section outlines the aim, main research question, and derived objectives of the research project. Finally, the last section provides an outline of the complete thesis, offering a brief introduction to each chapter and detailing the specific topics they will cover.

1.1 Key Concepts

This section explores key concepts related to haptic displays and their application in navigation. Haptic displays incorporate tactile sensations or feedback into devices to enhance user interaction and immersion. Understanding the terminologies associated with haptics and navigation is important for comprehending the subsequent discussions. The section delves into terminologies, the relationship between navigation and haptic displays, profiles of haptic displays, passive vibrotactile display for navigation, active proprioceptive display for navigation, evaluation of displays, and cross-comparison of displays.

1.1.1 Terminologies

The word “haptics” as a noun comes from the Greek word “haptikos”, which means “able to come into contact with”. The word made its way into the New Latin as “haptice” meaning “science of touch”. As an adjective, the word “haptic” indicates the inclusion of touch in any interaction. In the context of technology, haptics refers to the science and technology of incorporating tactile sensations or feedback into devices to enhance user interaction, and immersion in the case of virtual environments. The broad field of Haptic Technology deals with any technology that involves the sense of touch for input and or output (I/O) operations. Haptic devices as output devices are also called Haptic Displays. (Vaibhav et al., 2010)

Next, sense of touch related terminologies. Humans have five basic senses: sight, hearing, smell, taste, and touch. Through these senses, we experience the world around us. The sense of touch, as a basic skin-based sense, detects external stimuli: temperature, texture, pressure, vibration, and pain. This sense of touch is also known as the cutaneous sense. However, there are two more internal senses which work with the cutaneous sense: proprioception, and kinesthesia. The sense of proprioception tracks the position and the orientation of the body parts at a given time in space. Whereas the sense of kinesthesia tracks the movement of the body parts at a given time (NCBI, 2001; Sahyouni, 2019). The cutaneous sense on its own is a passive system; it can only receive stimulation. However, the cutaneous sense combined with the sense of proprioception and kinesthesia is an active system, meaning a body part can move actively to receive, seek, and give stimulation. The active touch allows a better understanding of the whole object, such as its shape and texture. It also allows a point-based understanding of an object, such as the temperature at the point of contact. (Gibson, 1962; MacLean, 2008; Mazella et al., 2018)

1.1.2 Navigation and Haptic Displays

Now, a few words on navigation. Navigation is an essential practice for various purposes. Whether it's finding our way in physical spaces, exploring new environments, avoiding obstacles in the real world, or navigating through a virtual world, the ability to navigate effectively plays a crucial role in our daily lives.

Navigation is done using two critical pieces of information: direction and proximity. Direction refers to the orientation or heading towards a particular destination or target. Proximity, on the other hand, relates to the concept of nearness or distance in relation to a specific point or object. Direction is important because it allows you to orient yourself and to plan your route or avoid obstacles. For example, if you know that you need to go north to reach your destination, you can avoid going south or east. Proximity is important because it allows you to estimate how long it will take you to reach your destination or an obstacle to avoid. For example, you can pace yourself based on the proximity information during navigation.

Direction and proximity information are the building blocks of the spatial relationships (egocentric and allocentric) between different locations and or objects. Egocentric relationships are where the reference point is based on the individual’s own body or self, whereas allocentric relationships are where the reference point is based on external landmarks or objects in the environment. These spatial relationships help the brain form a representation of the spatial environment that we are in. These spatial representations, also known as cognitive maps, are crucial for effective navigation (Pissaloux et al., 2017; Ekstrom and Isham, 2017; Ottink et al., 2022). Therefore, haptic displays for navigation commonly aim to convey direction and proximity information to assist the user.

During this research, direction and proximity were conveyed in the egocentric frame of reference using a clock face. Direction can also be conveyed using other methods such as cardinal directions (north, south, east, west), degrees on a compass, or spoken language terms (front, back, left, right). However, clock face was used because it is a common and intuitive method with a higher precision (12 distinct points and 360-degree reference). It provides a simple and universally understood reference point for indicating direction in relation to a central point. It is a mental model that most people are familiar with and an efficient method for communicating directions; for example, if an object is to the right and slightly ahead, it can be simply communicated as being located at 2 o’clock (Twyman et al., 2015).

Humans have created diverse tools for navigation, for example, tools based on vision such as a compass, global positioning system (GPS) based devices including mobile phones, and tools based on touch or tactile feedback such as smart canes and many other handheld devices. These tactile devices are also called haptic displays for navigation. Navigational haptic displays are used by the sighted population in multiple settings (Kappers et al., 2022), for example, where visual cues are obstructed or unavailable (Erp et al., 2005; Wang et al., 2018), or to complement visual cues to help with multi-tasking (Tsukada and Yasumura, 2004; Mercado et al., 2016; Hsieh et al., 2019), or for similar activities but in Virtual Reality (VR) (Spiers et al., 2023). Navigational haptic displays are also used by the visually impaired population in settings where a sighted person would also utilise them and more (Sorgini et al., 2018; A. Adilkhanov et al., 2022). The target user of such haptic devices can be anyone needing navigational instructions through their sense of touch in situations where, for example, multitasking is required (e.g., pilots, teleoperations, virtual environments, etc.) or Audio-Vision channels are unavailable (e.g., audio-vision related disabilities, firefighting, etc.). Therefore, navigational haptic displays are not mutually exclusive but rather can serve as complementary and assistive devices alongside other technologies or tools for a wide range of users. Improvements in haptic displays for navigation will benefit inclusively a diverse group of users.

1.1.3 Profiles of Haptic Displays

Although this research focuses on haptic displays for navigational applications, their potential extends beyond navigation alone. Haptic displays, in general, have found application in diverse fields, ranging from medical contexts (Choi et al., 2018) and assistive technologies (Sorgini et al., 2018) to educational settings (Hightower et al., 2019). Across these diverse applications, haptic displays exist in a wide variety of types (such as Vibrotactile, Electrotactile, Thermotactile, or Mechano-tactile), variations (such as single-element or multi-element), operational modes (such as active or passive), and forms (such as grounded, ungrounded, wearable, or handheld). Different attributes of a haptic display, such as its type, variation, mode, and form, have their advantages and disadvantages, which in turn impact the hardware design of the display and the type of haptic stimuli it can generate. For example, vibrotactile lends itself to wearable applications; however, the skin adapts to the vibration over time. On the other hand, mechano-tactile can help with the problem of skin's adaptability, but due to the bigger size of its components, this type lends itself to grounded applications.

1.1.4 Passive Vibrotactile Display for Navigation

In the context of navigation, specific profiles of haptic displays have been utilised more than others for varying reasons, such as cost, availability, wearability, complexity, performance, usability, etc. For example, ample studies have tried haptic belts for navigation and found them effective. These haptic belts are mostly passive, multi-element, vibrotactile, ungrounded, and wearable (Tsukada and Yasumura, 2004; Erp et al., 2005). On the other hand, a specific profile lacks investigation for being, potentially, too low in resolution for displaying spatial information (Kaczmarek et al., 1991; Wilkinson et al., 2019): passive, single-element, vibrotactile, ungrounded, and wearable haptic displays. If a haptic display based on this minimalist profile can communicate navigational information effectively, then it would bring desirable benefits of lower cost, simplicity of design, ease of availability, wearability, lower power consumption, etc. In addition to that, it will support the notion “less is more” in terms of the number of actuators and “more (quality) is better” in terms of the quality of the haptic stimuli. This research will test a passive, single-element, vibrotactile haptic display in the form of a wristband and a passive, multi-element, vibrotactile haptic display in the form of a belt to answer one of the research questions: how intuitive and effective is a passive single-element vibrotactile display compared to a passive multi-element vibrotactile display for navigation?

1.1.5 Active Proprioceptive Display for Navigation

Another profile that lacks examples of investigation in the published literature is of an active, single-element, proprioceptive, vibrotactile, ungrounded, and handheld or wearable haptic display. This profile of haptic displays would take advantage of the ability that allowed you to know where your thumb was pointing with your eyes closed: proprioception. A typical analogue stick, also known as a joystick, thumbstick, or control stick, is an application of this concept. Joysticks are typically used as an interface to input commands to a machine or computer; applications range from gaming controllers, and remote-controlled toys, to controlling machinery such as cranes, and robotic arms. The same joystick, but reversed, as an output interface would be a haptic display that would be utilising the body’s sense of proprioception to receive information. If a haptic display based on this multi-modal profile can communicate navigational information effectively, then it would also bring desirable benefits of lower cost, simplicity of design, ease of availability, lower power consumption, modular, handheld, etc. In addition to that, it may prove to be more effective and intuitive than passive haptic displays for the application of navigation. This research will test three variations of an active, single-element, proprioceptive, vibrotactile haptic display in the form of two joysticks and one dial-based to answer one of the research questions: how intuitive and effective is an active proprioceptive vibrotactile device for navigation?

1.1.6 Evaluation of Displays

To answer whether a haptic display that utilises proprioception, or any other type of haptic display, is effective and intuitive for displaying navigational information, a thorough evaluation must be done. In the published literature, the effectiveness and intuitiveness of haptic displays for navigation have been mostly narrowly evaluated. Effectiveness is evaluated based on a couple of objective measurements: accuracy/error rate and response time; in some cases, only accuracy is measured to evaluate a given haptic display for a given navigational task (Kappers et al., 2022). On the other hand, intuitiveness is evaluated using a prevalent, though implicit, assumption in the literature: if a device is effective, it must be intuitive. Subjective measures which would indicate the user experience, such as experienced mental workload and perceived usability of a haptic display, are not evaluated. Without taking subjective user experience into account, a full understanding of the effectiveness and intuitiveness of haptic displays is not possible (Jahedi and Méndez, 2014). For example, Sorgini et al. (2018) argues that many existing haptic devices suffer from a lack of acceptance by users. One of the reasons for the lack of acceptance is the high cognitive load imparted on the users by the haptic devices during stimuli interpretation. During this research, each haptic display will be evaluated using objective as well as subjective measures. Objective measures include accuracy, response time, and the rate of stimulus exposure, while subjective measures include experienced mental workload and perceived usability of the display. In addition, qualitative data will be captured through demonstrations conducted with both sighted and visually impaired individuals, as well as through informal interviews with the participants as part of the testing methodology.

1.1.7 Cross-comparison of Displays

Although there are some examples in the published literature where the haptic displays have been thoroughly evaluated, taking into account both objective and subjective measures (Bordegoni et al., 2012; Mercado et al., 2016; Hsieh et al., 2019), one issue that still remains is a lack of cross-comparison between different haptic displays. Many research projects follow a pattern of selecting a specific haptic display profile, such as active or passive, vibrotactile or mechano-tactile, as the primary focus. During the project, the design of the display evolves, and performance evaluations, comparisons, and conclusions are primarily focused on optimising that particular device. User-based objective and subjective evaluation of the haptic display is anchored to the first iteration of that display in the case of a within-subjects setting, while in the case of between-subjects, participants have no other reference but the display being tested. To address the issues related to the lack of cross-comparison of displays, this research will employ a comprehensive approach where each participant will be required to test five different haptic prototypes in five separate sessions, with one prototype being tested per session. This will allow for an insightful cross-comparison to answer the main research question: how intuitive and effective is an active proprioceptive vibrotactile display compared to a passive vibrotactile display for navigation?

1.2 Aims and Objectives

The ultimate aim of this research project is to contribute towards the understanding and, consequently, the improvement of designs and user experience of navigational haptic displays. This research tries to do that by pursuing a research question which has been formulated to address the issues pointed out earlier:

How Intuitive and Effective is an Active Proprioceptive Vibrotactile Device Compared to a Passive Vibrotactile Device for Navigation?

In order to address the above-mentioned research question effectively, the following objectives are pursued during this research project:

- Evaluate the effectiveness and intuitiveness of three classes of haptic displays (passive single-element; passive multi-element; and various active proprioceptive) for navigation.
- Compare the effectiveness and intuitiveness of these classes of haptic displays for navigation.
- Assess the objective measures such as accuracy, response time, and rate of stimulus exposure for each haptic display.
- Assess subjective measures such as experienced mental workload and perceived usability of the haptic displays.
- Incorporate qualitative aspects, such as demonstrations and informal interviews, throughout the research to gain a deeper, user-centred understanding of the haptic displays.
- Address the lack of cross-comparisons in the existing research on haptic displays for navigation.

1.3 Thesis Structure

This thesis presents different aspects of the research over seven chapters:

Chapter 2 provides a comprehensive overview of the field of haptic displays in the context of navigation. It begins with a brief introduction and then provides an overview of the field of haptics, including applications, working principles of haptic devices, components of the sense of touch, and the interaction of haptic devices with our sense of touch. The chapter then narrows its focus on haptics for navigation, highlighting relevant knowledge gaps in the published literature. Finally, the chapter presents research questions aimed at addressing the identified knowledge gaps.

Chapter 3 explains the methodology used to address the main and sub-research questions. The chapter explains each aspect of the methodology, including the experimental procedure, task design, prototype development, participant recruitment, data collection, and data analysis.

Chapter 4 focuses on the evaluation of passive vibrotactile devices for navigation. It specifically examines the performance of a haptic belt and a haptic wristband. The aim is to investigate their potential as navigational haptic displays and understand the impact of hardware and haptic cue differences on the reception of direction and proximity information. The chapter provides a detailed description of the experimental setup used to collect objective and subjective data for both devices. The results obtained for each device are presented and discussed, for each variable of interest: accuracy, time taken, repeats taken, experienced mental workload, and system usability score. Lastly, key findings from the informal interviews that were conducted at the end of each testing session are presented.

Chapter 5 evaluates the performance of three active proprioceptive devices (two joysticks and a haptic dial) as haptic displays for navigation. The aim is to investigate their potential as navigational haptic displays and understand the impact of hardware and haptic cue differences on seeking direction and proximity. It covers details of the experimental setup, presents and discusses results, and compares the performance of the given device locally. The results are presented in terms of accuracy, time taken, repeats taken, experienced mental workload, and system usability score. Lastly, key findings from the informal interviews that were conducted at the end of each testing session are presented.

Chapter 6 provides a comprehensive comparison of the effectiveness and intuitiveness of different haptic display prototypes tested for navigation, highlighting key findings and insights from the study. It takes each variable of interest and performs inferential statistics on the data (Hypothesis testing, Analysis of Variance, and Tukey’s Honestly Significant Difference) to draw conclusions. Lastly, key findings from the informal interviews that were conducted at the end of each testing session are presented.

Chapter 7 discusses the findings, conclusions, and future research possibilities of haptic displays for navigation based on this research. The contributions and limitations of the research project are also discussed, and suggestions are made for future research to build upon these findings and further enhance our understanding of haptic displays.

Chapter 2
Literature Review

At the highest level, the goal of this research project is to contribute towards the improvement and understanding of haptic displays in the context of navigation. The goal of this chapter is to describe and explain the route this research project took to achieve the research goal and the rationale behind taking that route.

This chapter provides a map in the form of an overview of the field of haptics, relevant published work, and, consequently, the location of this research project on that map. First, at a broader level, the overview will cover applications, working principles of the haptic devices, components of the sense of touch, and interaction of haptic devices with our sense of touch. Next, the chapter narrows its focus on the application of interest, i.e., haptics for navigation. Within this context, the chapter points out relevant knowledge gaps in the published literature. Finally, research questions aimed at addressing the identified knowledge gaps are given.

2.1 Search Strategy for Literature Review

In the process of developing this literature review, I conducted an extensive search to gather relevant scholarly materials. The search strategy encompassed various reputable databases, including Leeds Library Search, Web of Science, SCOPUS, and Google Scholar.

To ensure comprehensive coverage of the literature, the whole literature searching was divided into three stages: Field of Research (FoR), Area of Research (AoR), and Topic/Speciality of Research (SoR). Literature search during the FoR stage looked at haptics in its broadest sense, search was narrowed to haptics for navigation during the AoR stage, and, finally, search was further narrowed to haptics for navigation using active proprioception during the AoR stage.

Search strategy utilised a combination of specific keyword queries tailored to each stage of the literature search. These queries were designed to retrieve pertinent articles, journals, and conference proceedings related to each stage of search. These used different techniques to narrow or expand the search results; for example, phrase and proximity searching, truncation and wildcarding to include alternative endings for a word stem, and combining

Boolean operators. The literature search questions and keywords and phrases employed in the search process are given in Table 2.1.

Additionally, filters and inclusion/exclusion criteria were applied to refine the search results and ensure the selection of high-quality and pertinent sources. Depending on the stage of search, main filters included limiting date range (for example, no limit, last five years, last 10 years, etc.), subject (for example, engineering, technology, psychology, etc.), resource type (for example, journal-only, conference proceedings, books, theses, etc.), and language (for example, English-only).

In regard to inclusion/ exclusion criteria, it also varied in selectiveness depending on the stage of search. During FoR stage, the high-level searching, search results that were about haptics, haptic feedback, haptic sensing, or haptic interactions were considered irrespective of the target application, otherwise they were excluded from the review. During the AoR stage, the narrower-level of searching, search results that were about haptic feedback for communication and or navigation were considered, otherwise were excluded. Finally, during the SoR, the narrowest-level of searching, search results that were about active proprioceptive haptic feedback for communication and or navigation were considered, otherwise were excluded.

Table 2.1: Literature review search stages

Stage	Literature Search Questions	Keywords, phrases	Exclusion Criteria
FoR	How is **Haptic technology** being used in terms of **Haptic Displays**?	Haptic technology, haptics, haptic devices, haptikos. Haptic display, mechanotactile, electrotactile, thermotactile, haptic feedback, tactile feedback.	Is this item about haptic display? Is this item about Haptic Sensing? Is this item about Haptic Interaction? If “No” for all, exclude.
AoR	How is **Haptic technology** being used in terms of **Haptic**	Haptic communication, tactile communication,	Is this item about haptic display or interaction for

	Displays for **Communication** and or **Navigation**?	mechanotactile, electrotactile, thermotactile, vibrotactile, haptic navigation.	communication and or navigation? If “No”, exclude.
SoR	How are **active proprioceptive haptic displays** being used for **communication** and or **navigation**?	Active haptic display, Interactive haptic display, Proprioceptive, proprioception, kinesthetic.	Is this item about active Haptic display or interaction for communication and or navigation? If “No”, exclude.

At any stage, when an article was considered, multiple aspects were noted: Major field and the sub-field of application for the haptic device, target use case, method of stimulation employed, actuators used, and the body part used for the feedback. Furthermore, these aspects were used to categorise the literature review as shown visually in Figure 2.1, Figure 2.2, and Figure 2.3. This rigorous search process was essential in providing a solid foundation for the literature review presented in this thesis.

2.2 Applications

Haptic displays have applications in many fields. Figure 2.1 shows a few of the major applications and associated sub-applications with some examples from the published literature. This research focuses on haptic displays for navigation. The target user of the investigated haptic displays can be anyone who needs navigational guidance through their sense of touch—for example, pedestrian navigation in situations where visual or audio feedback is unavailable or unsafe, robotic teleoperations, and navigation scenarios in virtual reality.

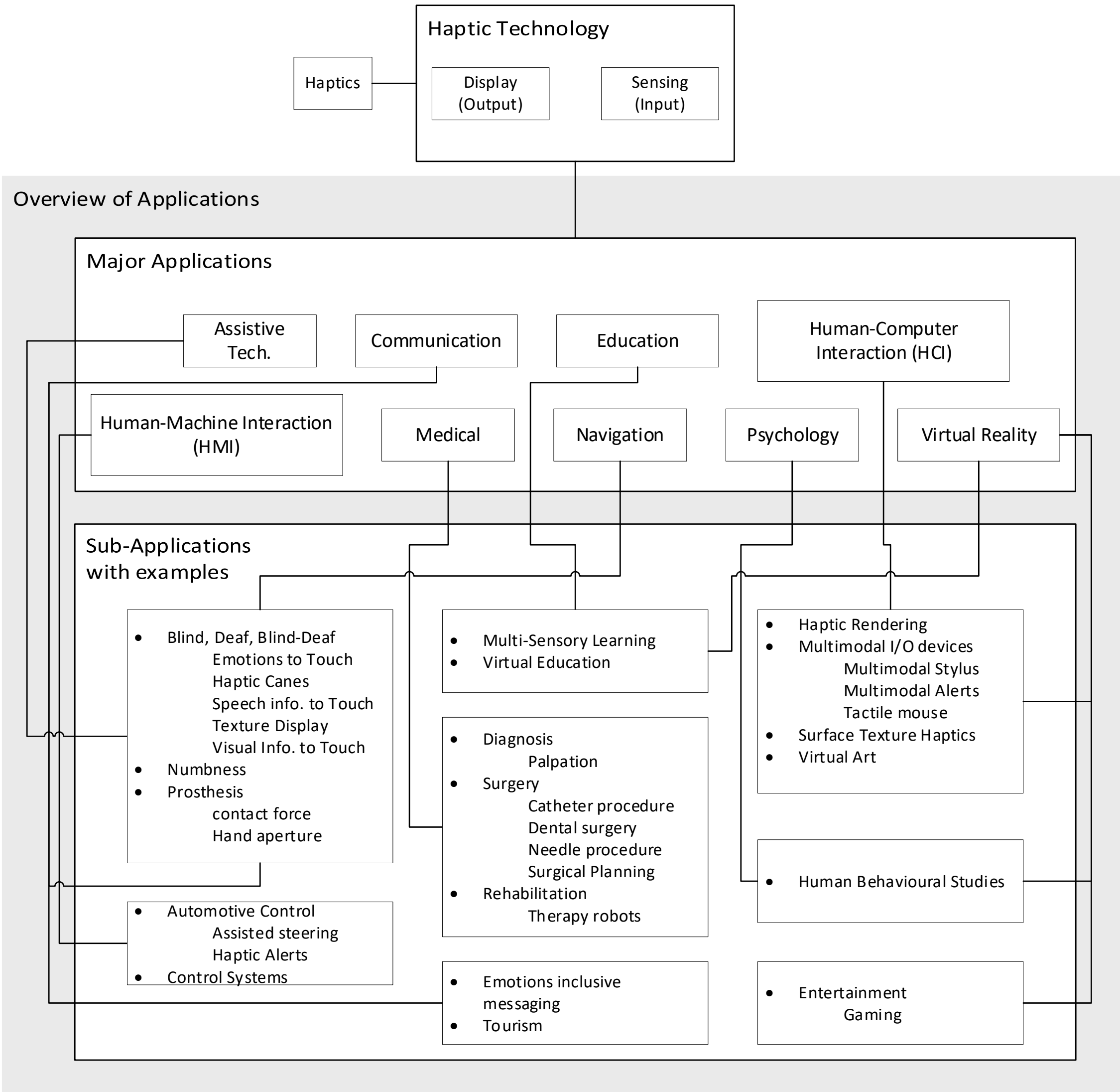


Figure 2.1: Overview of applications

Haptics is a key element of **assistive technologies**, especially for visually and auditory impaired populations. Use cases include communication of facial expressions (Buimer et al., 2018), internet access (Perfect et al., 2018), religious participation (Hussain et al., 2019), speech communication (Khambadkar and Folmer, 2014; Reed et al., 2018), **navigation** (Spiers et al., 2018; Khan et al., 2018; Ogrinc et al., 2018), and many more examples of haptics as part of assistive devices have been covered by various review articles (Hakobyan et al., 2013; Shull and Damian, 2015; Sorgini et al., 2018; Perfect et al., 2018; Khan et al., 2018).

Haptics is also used to enhance visual and or audio-based **communication**; for example, haptic displays can be used to communicate emotions haptically in addition to verbal and visual communication (Ceballos et al., 2018). Haptics has been explored as a medium to communicate alerts,

navigational instructions, and complicated information (Wang et al., 2016). This application of haptics continues to grow with the increasing adoption of smartwatches and mobile phones. Different techniques have been deployed to communicate navigational information through haptic displays – more on this in section 2.6.

Another enriching application of haptics is in the field of **education**. Adding haptics to visuals and audio can enhance the learning experience; for example, Edwards et al. (2018) used a head-mounted Virtual Reality (VR) display combined with haptic gloves to help pre-university students learn organic chemistry in a VR classroom. Whereas Hightower et al. (2019) used a TPad Phone combined with a haptic explorer app to enhance children's learning. Children took images and the app converted images into haptic feedback.

Human-Computer-Interaction (HCI) is a multidisciplinary field that focuses on the design, evaluation, and implementation of interactive computer systems for human use (Wania et al., 2006). To enhance HCI experience, HCI devices also incorporate haptics; for example, D. Chen et al. (2018) proposed a stylus-based multimode haptic display where vibrotactile and force feedback can enhance the user experience of interacting with screens. Whereas Shultz et al. (2018) designed a touch screen that can project texture-related data on the screen haptically. Strese et al. (2018) designed a haptic mouse which makes interacting with a computer more immersive because it can haptically display features like texture, hardness, temperature, and roughness. Burkhardt et al. (2018) investigated the use of haptics in an error detection application in the context of railway maintenance.

Human-computer interaction (HCI) for accessibility is a sub-field that focuses on designing, modifying, or enhancing HCI technologies and devices such that they can be used by people with disabilities. Examples range from screen readers and voice recognition software to tactile devices (Hakobyan et al., 2013; Zolyomi et al., 2017). For example, Turchet et al. (2021) found using arm-bands with haptic feedback a promising method to help visually impaired play music in a group; Morelli and Folmer (2014) used Nintendo Wii controller as a gesture-based haptic feedback HCI device to help visually impaired users play games such as Wii tennis and bowling; Hussain et al. (2019) used an off-the-shelf mobile and smartwatch to assist deafblind users with performing congregational prayers; Norberg et al. (2014) tested the use of morse code encoded as haptic cues to potentially make web browsing accessible for deafblind users; Zeng and Weber (2017) tested the presentation of tactile mobile maps and environmental accessibility information on pin-matrix displays to assist visually impaired navigate to point of interests, he found it a promising device and method if the device could be made portable; Rodriguez et al. (2019) tested a popular HCI (Novint Falcon), normally used as 3D haptic mouse, as an assistive device for navigation and shape perception tasks and found it effective; and Theil et al. (2020) tested haptic communication using a tablet for input and wearable vest with vibration motors for haptic feedback, researcher made an inaccessible touch screen of a tablet accessible by incorporating a tactile cover that provides tactile feedback for the user to draw haptic patterns on the touchscreen. The ongoing efforts outlined in these studies underscore the potential for HCI and haptic technologies to bridge accessibility gaps and enhance the daily lives of individuals with disabilities.

Furthermore, this research aligns with the guiding principles of HCI for accessibility, embracing user-centred approaches. It involves demonstrating ideas at different stages of the research and collecting both objective and subjective data to gain a deeper understanding of user experiences.

Haptics can also enhance **Human-Machine-Interactions (HMI)**; for example, Wang et al. (2018) showed that, during degraded visual feedback, haptic guidance helped drivers in keeping their cars in lane. Whereas, Erp et al. (2005) used haptics-based guidance in the context of helicopters and boats. Mercado et al. (2016) proposed the use of haptic displays as an additional channel for information for Unmanned Aerial Vehicle (UAV) operators.

Another key application of haptic displays is in the field of **Medicine**. Examples can be found in training, diagnosis, surgery, and rehabilitation applications. For example, palpation is a commonly used diagnostic method and is used for cues regarding the viscoelastic properties of tissue. Researchers have used a variety of techniques to haptically display tissue properties to facilitate palpation training of medical students (Rizzo et al., 2018; Talhan and Jeon, 2018). Whereas Kim (2018) used 2D imaging for skin roughness estimation which can be displayed for palpation via haptic devices to avoid secondary infection and skin damage. In terms of surgery, teleoperation heavily depends on haptic displays for a realistic experience. Surgical procedures that can benefit from haptic displays are, for example, teleoperated needle procedure (Han et al., 2018), pre-operative surgical planning (Halabi and Halwani, 2018), steering of nanorobots (Pacchierotti et al., 2018), and catheter procedure (Schecter et al., 2018; Zhang et al., 2018). Choi et al. (2018) has published a review article on the past, present, and future of telesurgery/teleoperation, the study covers important machines used in the field and Important parameters for the success of teleoperation in terms of implementation. Haptics is one of the parameters. Haptic displays are also an effective feature in the context of rehabilitation; for example, Baur et al. (2018) used haptic feedback for arm therapy and showed that addition of haptic feedback increased the motivation in the robot-assisted therapy.

Virtual reality (VR) is another industry that is interested in using haptic displays to enhance the user experience and immersion; for example, Kim et al. (2018) used a 7 degree of freedom manipulator as a haptic display to create a sense of touching a door and wall in virtual reality, Wang et al. (2018) used an elastomeric bladder based haptic display for terrain rendering in virtual reality, Chinello et al. (2018) used servo motors and vibrotactile motors to make a spherical wearable fingertip device to display stiffness and orientation of a surface being touched in virtual reality, while Lee et al. (2018) used DC motors and Pulley arrangements to create a haptic display that can be worn on fingers to manipulate objects in the VR.

2.3 Stimulation Methods

Different haptic devices use different stimulation methods to convey information to the users. The stimulation methods fall under three categories: mechanical, thermal, and electrical. Stimulation methods in the mechanical category stimulate the sense of touch (mechanoreceptors) through mechanical means such as forces, torques, displacements, vibrations, and momentums. Thermal stimulation methods stimulate another group of receptors present in the skin called thermoreceptors to convey information using temperature changes. Finally, the stimulation method in the electrical category can stimulate both groups of sensory receptors (mechanoreceptors and thermoreceptors) electrically without any moving parts (Rock, 1984; MacLean, 2008; Goldstein and Cacciamani, 2021). Figure 2.2 shows an overview of stimulation methods.

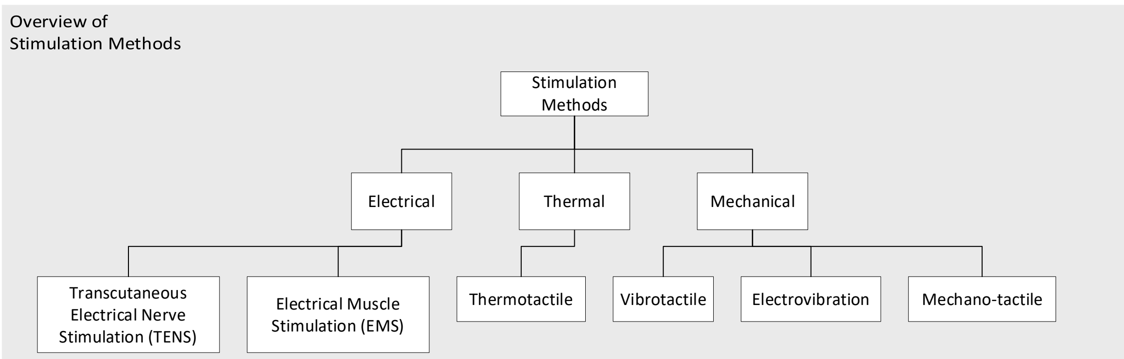


Figure 2.2: Overview of stimulation methods

Below is a brief introduction to each type of stimulation method and the associated subcategories, advantages, and disadvantages.

2.3.1 Electrical Stimulation

Transcutaneous Electrical Nerve Stimulation (TENS or TNS), also commonly known as Electrotactile, and **Electrical Muscle Stimulation** (EMS) are electrical stimulation methods. This method also engages the skin-based cutaneous sense (see section 2.4). Electric current is passed through the skin using electrodes to electrically stimulate the mechanoreceptors present in the skin to create tactile sensations (Pamungkas and Ward, 2016), or muscle contractions in the case of EMS. TENS is most common in the field of prostheses (Arakeri et al., 2018), while EMS is common in rehabilitation-related applications (Mavroidis et al., 2005). The advantages of this method are non-moving parts, size, weight, cost, and power requirements; for example, Teslasuit uses both to give haptic feedback (Teslasuit, 2022). On the other hand, the disadvantages are unpleasant sensations, such as itch, pinch, sting, and sharp burning pain. Moreover, this method requires fine-tuning of an extensive range of parameters, such as voltage, current, waveform, electrode size, material, contact force, skin location, thickness, and hydration (Kaczmarek et al., 1991; Kajimoto et al., 2003).

2.3.2 Thermal Stimulation

Thermotactile is a thermal method of stimulation. This method also engages the skin-based cutaneous sense of temperature as a channel to deliver information by mainly using Peltier elements for actuation.

Peltier devices are based on the Peltier effect which in turn is an aspect of the thermoelectric phenomenon. The Peltier effect is named after its discoverer, Jean Charles Athanase Peltier. When an electric current is passed through a junction of two materials, one side of the junction becomes cooler while the other side becomes hotter, this effect is called the Peltier effect (Labcentre, 2023; Britannica, 2023).

Peltier elements are available in various sizes and shapes. The main advantage of the Thermotactile method is that actuators are lightweight and small, lending themselves to wearable applications. Thanks to these advantages Peltier elements have been used, for example, in a suit (Teslasuit, 2017), glove (Kammermeier et al., 2004), and as a decorator display to stick on objects (Ishizuka et al., 2018). However, there are three main disadvantages: the slow cooling and heating rates of the actuators, the human skin's low resolution to detect temperature, and the skin's fast adaptation to temperature (Kappers and Plaisier, 2019).

2.3.3 Mechanical Stimulation

Electrovibration is a mechanical stimulation method. This method uses electrostatic force between an insulated electrode and the skin in contact to engage the skin-based cutaneous sense (see section 2.4). For example, the electrostatic force induces a frictional force between the fingertip and the insulated electrode. This frictional force shears the skin, leading to a texture sensation. The electrostatic force depends on the periodic change in voltage applied to the insulated electrode; a higher value of applied voltage creates a greater electrostatic force, resulting in a higher value of induced friction and hence a particular texture sensation. Therefore, the method is mainly limited to the display of textural information (Altinsoy and Merchel, 2012).

This method has certain advantages, for example, lack of moving parts, simple construction, and the display based on this method can be in the form of a thin, flexible, transparent sheet; for example, to make a haptic table (Emgin et al., 2018), display texture on a mobile device (Altinsoy and Merchel, 2012), or attach haptic displays to external objects (Ishizuka et al., 2018). However, the main disadvantage which prevents it from being used in wearable technologies is that the voltages required for good sensations are very high; for example, values can range from 30 Volts to 250 Volts. Such high voltage across an insulated electrode in contact with a human body requires higher safety considerations and leads to bigger and heavier battery sizes.

Vibrotactile is one of the mechanical stimulation methods and a favourite in many applications, including navigation. This method uses vibrations to engage the skin's cutaneous sense to deliver information. It employs three types of actuators: rotating electromagnetic, linear electromagnetic, and non-electromagnetic actuators (Choi and Kuchenbecker, 2013).

Eccentric Rotating Mass (ERM) vibration motors, the rotating electromagnetic type, depending on the shape, are also called pancake, coin, or barrel motors. This type of motor delivers vibration due to displacements in two axes (XY plane: parallel to the skin) as the eccentric mass rotates in the motor casing. The advantages are size, weight, and reproducibility of stimuli; for example, researchers have used ERM vibration motors in vests (Adebiyi et al., 2017), belts (Buimer et al., 2018), gloves (Hsieh et al., 2019), and wristbands (Wang et al., 2016). On the other hand, the main disadvantage is the intertangled amplitude and frequency of vibrations. The amplitude cannot be adjusted independently of frequency and vice versa (Precision Microdrives, 2019).

Linear Resonant Actuator (LRA) vibration motors, the linear electromagnetic type, can look similar to ERM vibration motors, but they deliver vibration due to displacement in one axis (Z-axis: perpendicular to the skin). There are two types of LRAs: solenoid-based, and voice-coil-based. Solenoid-based LRAs contain a coil with a ferromagnetic piece that moves, whereas voice-coil-based contains a permanent magnet that moves in a coil. For example, C2 tactors (Engineering Acoustics, Inc.) are an example of a widely used solenoid-based LRA; Haptuator-original, Haptuator-redesign, and HapCoil-One (Tactile Labs) are examples of voice-coil based LRAs. The main advantage of LRAs over ERM vibration motors is the independent control of the amplitude and frequency parameters (Jones and Sarter, 2008). LRA are a better option in applications like touchscreen where the user will experience a direct vibration in the direction of the pressed finger rather than perpendicular to press in the case of the ERM; for example, touchscreens and auto dashboard panels (Precision Microdrives, 2019). However, this advantage makes LRA vibration motor design more complex and the cost more expensive (Choi and Kuchenbecker, 2013). Moreover, it requires alternating current rather than direct current to operate, complicating its integration into designs (Precision Microdrives, 2019).

Non-electromagnetic actuators used by haptic displays are based on a range of principles, for example, the piezoelectric effect (Kamigaki et al., 2017; Emgin et al., 2018), electroactive polymers (Cruz et al., 2018), pneumatics (C. M. Nunez et al., 2022), and shape memory alloys (Pissaloux et al., 2017). These actuators need further research and innovation to become a viable option for haptic displays from size, complexity, cost, portability, power, and reproducibility of stimuli point of view.

The ERM vibration motors' advantages, such as simple design, size, weight, power requirements, ease of integration during prototyping, adequate vibration strengths, cost, and ease of availability, make them a preferred choice in general and over LRA and other non-electromagnetic vibration devices. However, the main disadvantage of the vibrotactile method, in general, is the human skin's adaptation to the vibrations.

Mechano-tactile is another mechanical stimulation method. It is the most intuitive method because it engages the sense of kinesthesia and or proprioception in addition to the cutaneous senses (see section 2.4). Mechano-tactile devices rely on larger assemblies of actuators and moving parts, such as servo motors, pully systems, gears, dials, and mechanisms (Kammermeier et al., 2004; Kim et al., 2014; Kim et al., 2014; Walker et al., 2018; Spiers et al., 2018; Rossi et al., 2019; Rodríguez et al., 2019). Popular devices such as Phantom, Omega series, Geomagic Touch X, Falcon, and similar fall under this category. These components produce more significant scale forces, torques, displacements, and momentums. In contrast, it is the least wearable-friendly out of all the other options for the same reason: the size, weight, and hard materials of the components lead to cumbersome and uncomfortable designs (Fontana et al., 2018). However, due to the ongoing miniaturization of moving parts, these disadvantages are likely to be temporary.

2.4 Components of Touch: Cutaneous, Proprioception, Kinesthesia

The sense of touch is a complex system of many interlinked sensory subsystems. The relevant subsystems are the cutaneous system, kinesthesia, and proprioception. Each subsystem deals with a different type of stimuli. These subsystems are interlinked and work together during most of our activities (Rock, 1984; MacLean, 2008; Goldstein and Cacciamani, 2021):

Cutaneous (the sense of contact) is based in the skin. It deals with pressure, contact, vibration, temperature, and pain stimuli. When people use the term sense of touch in everyday communication, they refer to the cutaneous sense.

Kinesthesia (the sense of movement) is based in the joints and muscles. It deals with the body and its parts’ movement (Sahyouni, 2019).

Proprioception (the sense of position) is also based in the joints and muscles. It tracks the body and its parts’ position in space (Sahyouni, 2019).

For example, with their eyes closed, most people can sense where their nose is relative to their hands (sense of position: Proprioception); they can move their hands accurately to touch their nose (sense of movement: kinesthesia); they know on contact that their hands have reached their nose (sense of contact: cutaneous).

Each stimulation method discussed in section 2.3, targets one or more of these subsystems. TENS, EMS, Electrovibration, Vibrotactile, and Thermotactile stimulation methods target the cutaneous system to deliver information. In contrast, the Mechano-tactile stimulation method engages the sense of kinesthesia and or proprioception in addition to the cutaneous system.

For example, a white cane is an active (see section 2.5) mechano-tactile-based haptic display for obstacle detection during navigation. It engages all three components of touch in an active mode: the sensation of a cane’s position with respect to the body is proprioception engaged; the sensation of a cane’s movement, for example, from right to left following a non-arbitrary trajectory is kinesthetics engaged; and the sensation of a cane’s contact with the ground is the cutaneous sense engaged.

Manual sign language is an example of a human hand functioning as an active haptic display for communication by involving all three components of touch: For example, proprioception detects the orientation of the hands; Kinesthetics detects the movements of the hands; Cutaneous sense detects the contact.

Figure 2.3 summarises the stimulation methods, commonly used actuators by each category, the subsystem(s) of touch engaged, and the commonly involved body parts. The body parts used by the haptic displays range from head to toe (Shull and Damian, 2015; Pacchierotti et al., 2017; Sorgini et al., 2018; Xia, 2018; Kappers and Plaisier, 2019; A. Adilkhanov et al., 2022; Kappers et al., 2022).

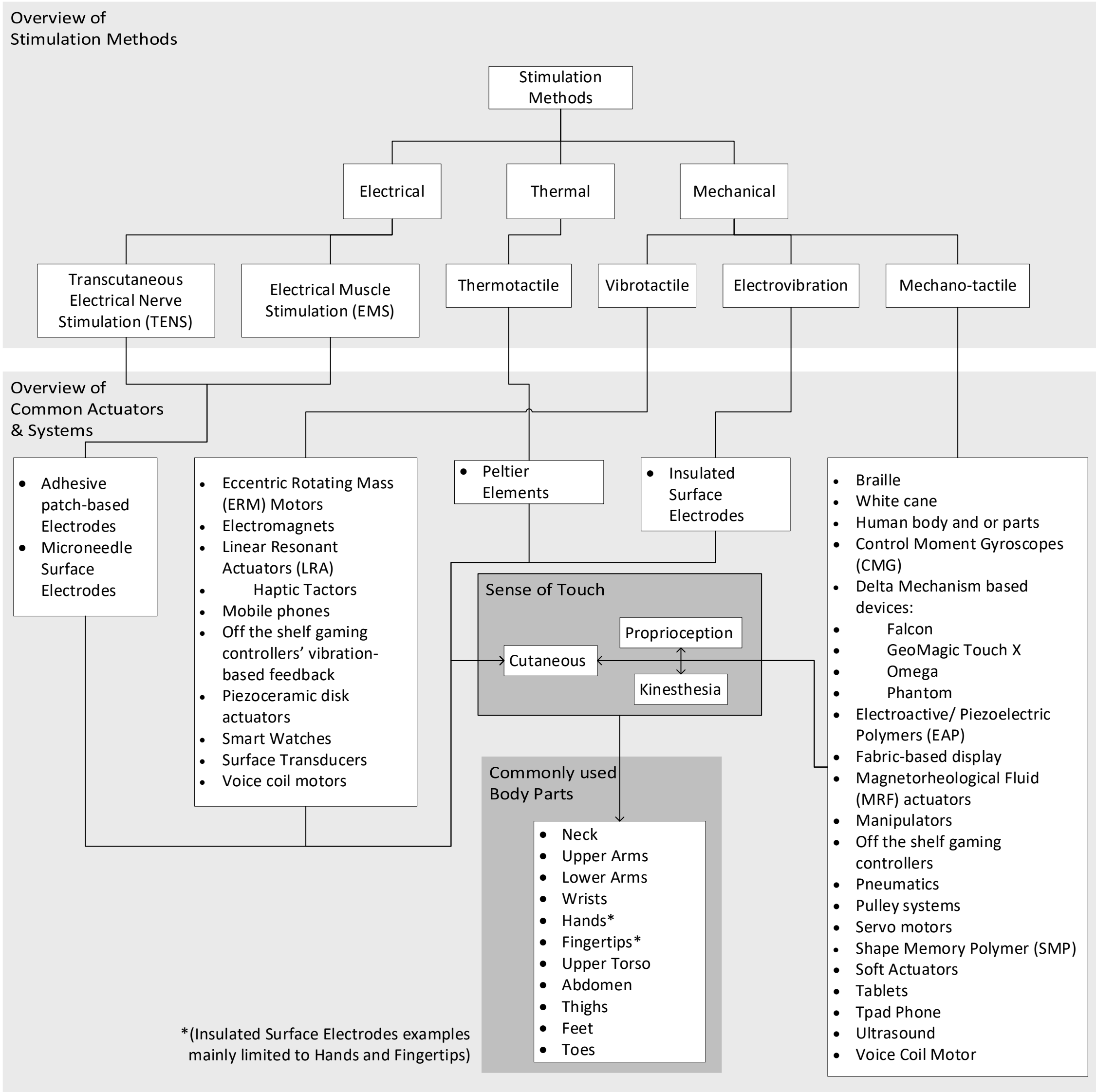


Figure 2.3: Overview of stimulation methods, actuators, components of touch, and commonly used body parts

2.5 Modes of Interaction: Passive, Active

Humans engage their sense of touch in two modes: passive and active. A person receives tactile stimulation in passive mode, whereas in active mode, a person seeks tactile stimulation, making active mode an exploratory mode (Gibson, 1962; Nomura and Sakamoto, 2013; Mazella et al., 2018; Rodríguez et al., 2019). Figure 2.4 shows a passive and an active user as block diagrams:

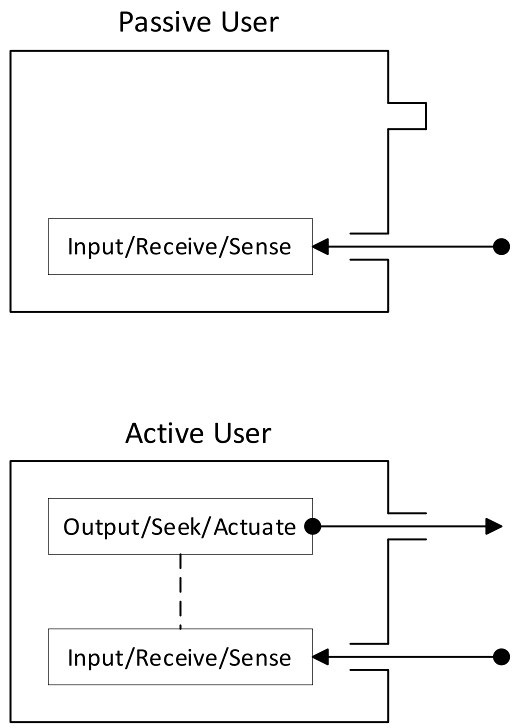


Figure 2.4: Modes of a user

Haptic devices can be passive or active in relation to the user. A passive haptic device solely outputs tactile stimuli to the user. In contrast, an active haptic device not only provides output in the form of tactile stimuli but also reads input from the user. For example:

Passive interaction: Imagine a plain wristband that vibrates every hour without any user initiative. In this case, the wristband is passive, and the user is also passive. The wristband does not require input from the user but delivers vibrations. Simultaneously, the user does not actively seek or initiate any action but receives vibrations.

Active interaction: Now, consider an alternative version of the wristband that requires the user to touch it before it vibrates to indicate the current hour. In this scenario, the wristband is active, and the user is also active. The wristband takes input from the user and subsequently delivers vibrations, while the user actively seeks or initiates the interaction and receives the vibrations in response. In any other case, the interaction would be passive, indicating that either the user does not initiate the touch despite the wristband being active or the user is active, but the wristband only vibrates every hour.

Figure 2.5 shows a passive and an active haptic device as block diagrams, and Table 2.2 summarises the possible interactions between a given haptic device and the user:

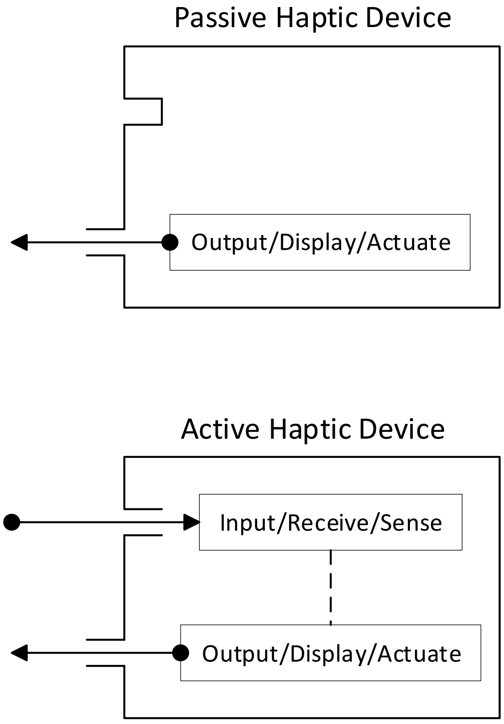
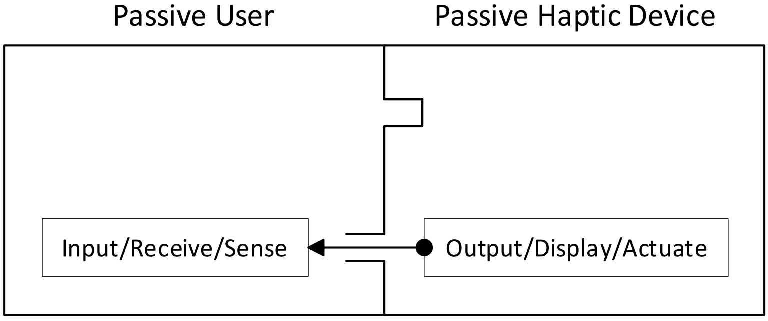
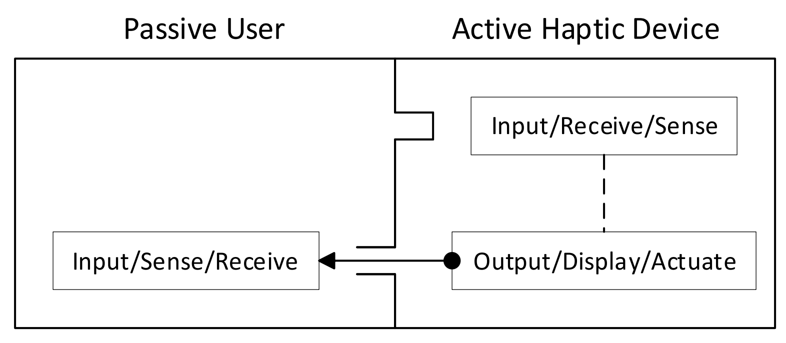
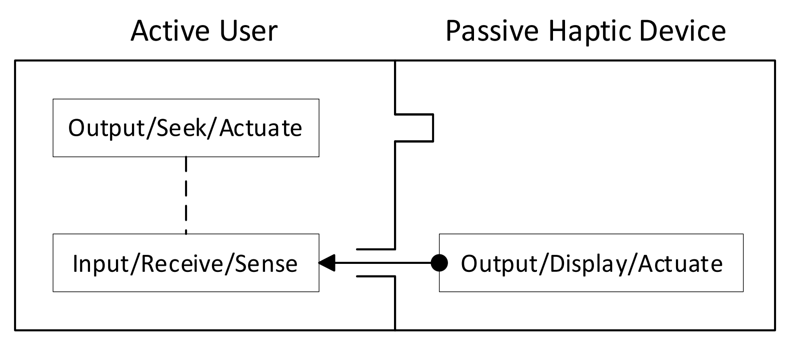
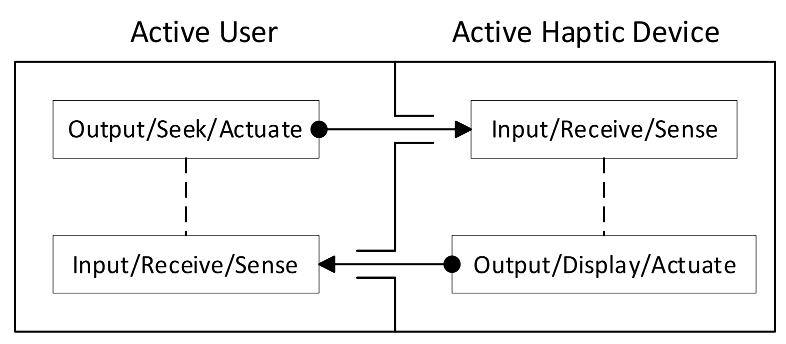


Figure 2.5: Modes of a haptic device

There are four possible user and haptic device interaction scenarios, as shown in Table 2.2. However, most examples in the existing literature are of passive interactions.

Table 2.2: Modes of interaction

Scenario label (User, Device)	Scenario	Resulting Interaction
PP		Passive

PA		Passive
AP		Passive
AA		Active

2.6 Haptic Devices for Navigation

As mentioned previously, this research focuses on haptic devices as navigational aids. Navigation is a complex process of accurately ascertaining one's position, planning, following a route, and avoiding obstacles. However, the navigator needs two essential pieces of information throughout the process: direction and proximity. These two units are fundamental in any aspect of navigation. So, the primary objective of any navigational haptic device is to communicate these two pieces of information effectively to the user.

Important characteristics of a navigational haptic device are that it needs to be wearable, portable, low-cost, intuitive, and effective. Wearability can add advantages such as hands-free operation, ease of access, discreetness, versatility, accessibility, and embodiment (Velázquez, 2010; Fontana et al., 2018; Gay et al., 2020). Wearable devices can be worn in a variety of ways such as a piece of garment, belt or even hang off a belt and accessed when needed, carried in a pocket, worn as a jewellery etc. (Picard and Healey, 1997;

Tsukada and Yasumura, 2004). Wearable haptic devices have shown to improve function in a variety of applications ranging from rehabilitation and prosthetics to navigation (Shull and Damian, 2015). A wearable haptic device has at least four design qualities: form factor, weight, impairment, and comfort (Pacchierotti et al., 2017). For example, a good wearable haptic device is compact, lightweight, does not restrict body motion, feels comfortable to wear/hold, and adapts to the wearer's body size. A portable device is ungrounded and does not need extra external infrastructure to operate, for example, a grounded device may require a camera to keep track of the body. A low-cost design ensures favourable chances of adoption, further improvements, and testing. An intuitive device imparts a lower cognitive load and is easy to use and learn. Lastly, an effective device displays accurately, quickly, and reliably perceivable directions and proximity cues to the user.

For reasons discussed earlier (see section 2.3), most wearable, portable, and low-cost haptic devices for navigation are passive and vibrotactile. For example, common passive vibrotactile devices are variations of a haptic belt and wristband. Vibrotactile belts and wristbands are generally multi-element devices, meaning they have multiple vibration motors along the circumference of the belt or wristband. Researchers have tested haptic belts and wristbands in different settings and found them effective for navigation. In the case of a haptic belt, a vibration pulse generated by a specific element positioned around the waist would represent a direction. For example, McDaniel et al. (2008) used a belt to convey the position of a person to whom the visually impaired wearer was speaking; Erp et al. (2005) also used a belt to communicate directions and distance, aiding the user in navigating a helicopter and a boat; Tsukada and Yasumura (2004) also tested a haptic belt for pedestrian activities that include navigating, such as navigation from one point to another, pointing in the direction of points of interest, locating lost items. Similarly, Wang et al. (2016) assessed the suitability of a wristband for information communication and found it as effective as complex vibration designs; Bosman et al. (2003) used two wristbands to aid navigation; Paneels et al. (2013) designed a novel multi-element wristband for navigational application; and commercially available assistive bands can also provide navigational instructions, such as Sunu band (Sunu Band, 2023) and Wayband (Wayband, 2023).

2.7 Identified Gaps in Knowledge

The area of haptic devices for navigation has seen significant advancements in recent years (Sorgini et al., 2018; A. Adilkhanov et al., 2022; Kappers et al., 2022), with a focus on multi-element vibrotactile devices and passive mechano-tactile systems. However, there are still important gaps in the literature that need to be addressed. This section aims to shed light on four key areas where investigation and evaluation are lacking: the potential of single-element passive vibrotactile devices for navigation, the effectiveness of active proprioception in haptic displays for navigation, the need for a thorough evaluation, and cross-comparison of different haptic devices. By exploring these gaps, research can gain a deeper understanding of the intuitiveness, effectiveness, and usability of haptic devices for navigation, ultimately paving the way for improved designs and enhanced user experiences.

2.7.1 Lack of investigation of single-element passive vibrotactile devices for navigation

There is a lack of thorough investigation of single-element passive vibrotactile devices for navigation, for example, a wristband with only one vibration motor.[1] Can a single-element passive vibrotactile wristband, intuitively and effectively, display directions and proximity?[2] The lack of thorough investigation of a single-element display may be rooted in an untested notion that multi-elements can present spatial information better than single-element (Kaczmarek et al., 1991; Wilkinson et al., 2019). A thorough investigation of a passive single-element vibrotactile display is important for two reasons: it is more wearable, portable, and low-cost than alternatives; it is the most basic type of vibrotactile display and can act as a reference point for comparing the intuitiveness and effectiveness of other designs of haptic devices for navigation.

2.7.2 Can active proprioceptive device make the haptic display of direction more effective?

A growing number of studies are focused on passive mechano-tactile devices for navigation. These devices are mainly kinesthetic, a subset of mechano-tactile, that delivers information through a forced motion of some body part. Researchers have labelled the devices intuitive, such as Novint Falcon, Omega3, and Phantom. Their most common application is as human-computer

[1] Knowledge-gap-1: lack of investigation of single-element passive vibrotactile devices for navigation.

[2] Sub-research-question-1: how intuitive and effective is a passive single-element vibrotactile device for navigation?

interaction devices, and are generally desktop devices (grounded) and, therefore, neither wearable nor portable. Furthermore, they are expensive to buy or construct. However, the ongoing miniaturisation of moving parts has allowed wearable and portable (ungrounded) kinesthetic devices for navigation to emerge, but the cost to construct them and commercial availability is still an issue. For example, kinesthetic devices use Control Moment Gyroscopes (CMG) (Bordegoni et al., 2012; Walker et al., 2018), exoskeletons (Pacchierotti et al., 2017), and servomotors with small moving parts (Spiers et al., 2018).

On the other hand, active proprioceptive devices, which are also part of the mechano-tactile category, lack investigation as navigational haptic devices. These devices deliver information using the body part's sense of position and orientation. For example, a study (Khambadkar and Folmer, 2014) explored using an active proprioceptive device as a haptic communication aid for deafblind users. The off-the-shelf gaming controller came with an accelerometer and a gyroscope to detect the hand's orientation. Researchers mapped different orientations to alphabets and a sequence of orientations translated into a word. The inspiration for their technique came from flag semaphores used in the navy to communicate information over a distance. However, the investigation of active proprioception in the context of navigation is a gap in the literature.[3]

The sense of proprioception maps intuitively with navigational directions. For example, in everyday life, when asked for directions, people are intuitively guided by pointing in the correct direction. Another common example is analogue joysticks for giving directions in gaming, control machines, and remote-control toys. Joysticks are intuitive and effective in actively giving directions because they map well with the user's sense of proprioception. However, can the reverse be true too, that is, can an active proprioceptive device, like a joystick, intuitively and effectively display directions?[4]

2.7.3 Lack of thorough evaluation of haptic devices

So far, this chapter has described that, in terms of hardware design, a navigational haptic display should be wearable, portable, and low-cost, whereas, in terms of usage, it should be intuitive and effective. This subsection

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[3] Knowledge-gap-2: lack of investigation of active proprioceptive vibrotactile devices for navigation.

[4] Sub-research-question-2: how intuitive and effective is an active proprioceptive vibrotactile device for navigation?

discusses evaluating the usage characteristics of a given device: intuitiveness and effectiveness.

Most hardware design characteristics (wearability: form, size, weight, impairment-obstructs motion or not; portability: ungrounded or not; cost: the total price of individual parts; and comfort) are self-explanatory and easy to evaluate. However, the usage characteristics (intuitiveness and effectiveness) require a clear, explicit definition.

In many examples of literature, researchers do not clearly and explicitly define the usage characteristics. Their evaluation of the effectiveness of a device is primarily based on two objective variables: accuracy and response time – in some cases, only accuracy. Furthermore, a prevalent assumption in the literature compounds this narrow objective evaluation of effectiveness: if a device is effective, it must be intuitive and vice versa. This narrow objective method of evaluation prevents a deeper understanding of a haptic device's intuitiveness and effectiveness for a task (Jahedi and Méndez, 2014). This understanding, by having both types of measurements, will allow better user-centred design iterations aimed at improving haptic displays for navigation. A thorough evaluation of navigational haptic devices is a gap in the literature.[5]

This research project addresses the gap by defining the usage characteristics as a set of subjective and objective measures: intuitiveness as a subjective measure and effectiveness as an objective. It links effectiveness to three objective variables: accuracy, response time (time taken), rate of stimuli exposure (number of repeats taken), and intuitiveness to two subjective variables: overall mental workload experienced and perceived system's usability. Chapter 3 further discusses the experimental methodology.

2.7.4 Lack of cross-comparisons

Finally, another gap in the literature is related to comparing navigational haptic devices.[6] For instance, many research projects focus on a specific type of haptic device (e.g., active or passive, vibrotactile or mechano-tactile); the device's design evolves during the project; evaluation is objective and narrow; comparison and conclusions are local optima for that one device. In some cases, subjective measures are also part of the evaluation process; however, users lack experience of using another haptic device as a reference, and, as a

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[5] Knowledge-gap-3: thorough evaluation of the haptic devices.
[6] Knowledge-gap-4: cross comparison of the haptic devices.

result, evaluation lacks relativity. The lack of cross-comparison of displays prevents understanding user preferences, relative usage characteristics, and global optima of different types of navigational haptic devices.

This research addresses this gap by evaluating and then cross-comparing the following modes and types of haptic devices in the context of navigation:

- Passive single-element vibrotactile
- Passive multi-element vibrotactile
- Active proprioceptive vibrotactile (joystick with a round rim)
- Active proprioceptive vibrotactile (joystick with an octagonal rim)
- Active proprioceptive vibrotactile (dial)

2.8 Conclusion

The passive single-element vibrotactile device serves as a reference (the simplest type of haptic device) and a novel way of displaying direction and proximity using numerosity and chunking. The passive multi-element vibrotactile device acts as another reference (a popular type of haptic device). The active proprioceptive vibrotactile devices proposed are another novel way of displaying navigational information. Chapter 3 further discusses each device.

This research project evaluates these different types of devices from two broad categories (Passive vibrotactile and Active proprioceptive vibrotactile) and compares the performance across objective and subjective measures to address the main research question: How intuitive and effective is an active proprioceptive vibrotactile device compared to a passive vibrotactile device for navigation?[7]

[7] Main-research-question: how intuitive and effective is a active proprioceptive vibrotactile device compared to a passive vibrotactile device for navigation?

Chapter 3
Methodology

The previous chapter identifies and explains the relevant gaps, sub-research questions, and the main research question: How intuitive and effective is an active proprioceptive device compared to a passive vibrotactile device for navigation? This chapter explains the methodology used to address this research question.

The components of the methodology follow from the elements of the research question as shown in Figure 3.1. The following sections explain each aspect.

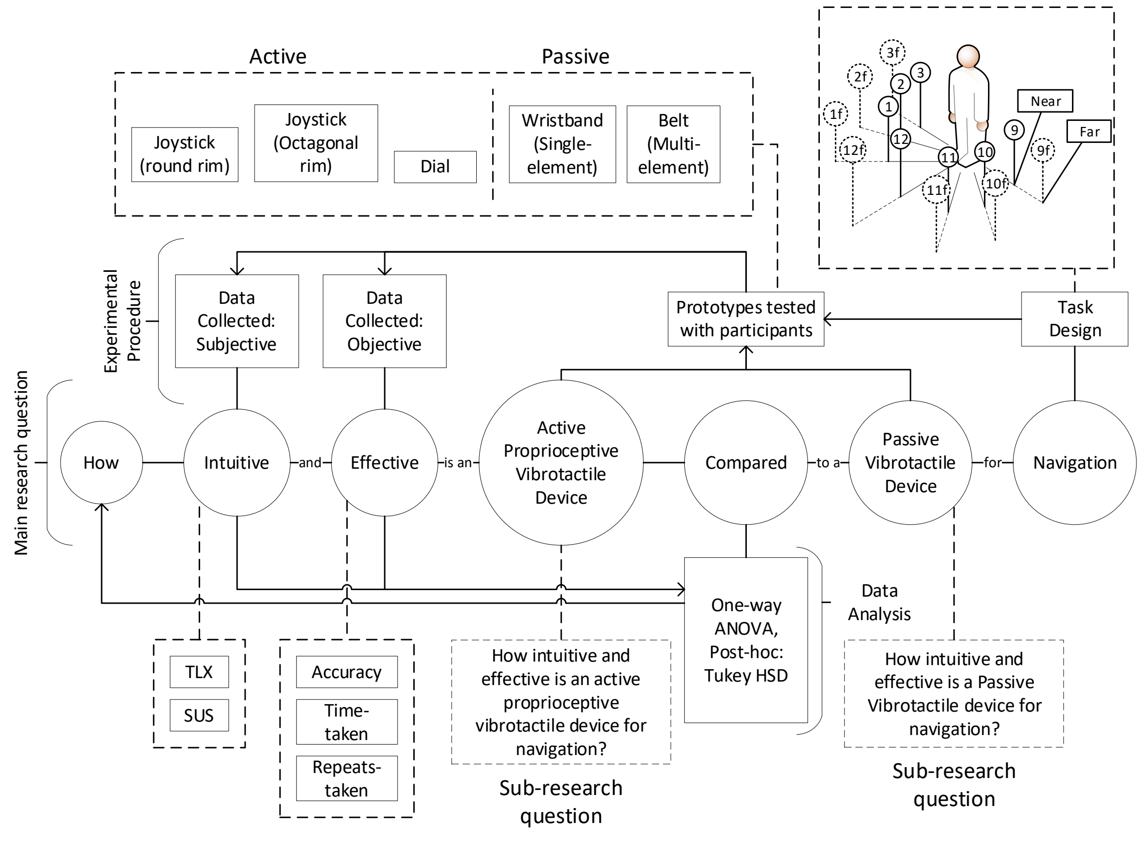

Figure 3.1: Overview of the methodology, its components, and the main research question

3.1 Demonstrations

The research project involved several demonstrations of the prototypes to a diverse group of potential users, including both sighted and visually impaired. These demos were held at various locations, such as the Affective Laboratory at the University of Leeds, homes, a community centre, and a school. During these interactive demos, users had the opportunity to try the prototypes, ask questions, and give their feedback, suggestions, needs, and concerns. These meetings were very informative and engaging. For instance, a haptic dial prototype was included and tested as a result of suggestions by a visually impaired user and a sighted user who preferred a dial over a thumbstick. Another visually impaired user liked the octagonal joystick and thought it could be useful for ball tracking during his golf sessions. Although the information collected from these demonstrations did not contribute to the quantitative analysis, it provided fresh perspectives, identified potential applications, highlighted areas for improvement, and brought attention to usability concerns.

3.2 Participants

Twelve sighted individuals between the ages of 23 and 59 were recruited for the study: all participants were right-handed, six males and six females, and a mean age of 39 ± nine years of standard deviation. This study was approved by the University of Leeds's internal research ethics committee. Each participant gave informed consent.

The selection criteria used was to recruit participants from the researcher's social network. The convenience sampling approach was used as it was challenging to access broader population due to covid related restrictions as well as general reservation among population (after restrictions) to participate in studies. Given the circumstances, researcher tried to recruit a diverse group of participants from their social network that would represent a broad range of characteristics relevant to the research. These participants were selected considering their varying ages, educational backgrounds, and levels of technological familiarity as shown in the Table 3.1.

Table 3.1: Sample composition

Participant no.	Age	Gender	Educational Background	Familiarity with Tech.
P1	23	Male	Bachelors	Medium
P2	28	Male	School	Low
P3	34	Female	Masters	Medium
P4	32	Male	PhD	High

P5	33	Male	Masters	High
P6	33	Female	Masters	Medium
P7	36	Female	PhD	Medium
P8	46	Female	Bachelors	Low
P9	35	Male	PhD	High
P10	29	Female	Masters	Medium
P11	29	Female	PhD	Medium
P12	59	Male	School	Medium

Twelve participants individually tested each of the five prototypes in separate sessions, each session occurring on a different day. The order of exposure to haptic prototypes were counterbalanced as shown in Table 3.2. This was done to ensure that any potential effects of the order on the participants' performance were evenly distributed and not biased by a specific order.

Table 3.2: Order of prototypes testing

Participant no.	Session 1	Session 2	Session 3	Session 4	Session 5
P1, P2					
P3, P4					

P5, P6					
P7, P8					
P9, P10					
P11, P12					

3.3 Prototypes

The tested prototypes are divided into two groups: Passive vibrotactile and Active proprioceptive vibrotactile. The passive group contains two prototypes: a wristband (single-element) and a belt (multi-element), while the active group contains three prototypes: a round-rimmed joystick, an octagonal-rimmed joystick, and a dial.

The following subsections describe each prototype in terms of hardware and corresponding haptic cues' (stimuli) design.

3.3.1 Prototype Development

During the exploratory phase of this research project, different haptic methods were explored. The exploratory work started with a passive single-element vibrotactile device in the form of a wristband. The idea of using a single vibration motor to convey direction and proximity was already under investigation by another closely aligned project called SUITCEYES. This PhD research conducted a pilot study to test the idea in the first instance. At the same time, started investigating other devices and their different applications such as multi-element vibrotactile, electrotactile, thermotactile, and mechanotactile.

In terms of hardware, the haptic wristband used during the pilot study consisted of a band that employed a single vibration motor. Concerning the haptic stimuli design, direction and proximity were conveyed using one-second-long vibration patterns to represent directions, while the intensity difference was used to represent proximity. The pilot study recruited ten participants, and the mean accuracy observed during the pilot study was 44%. This result served as the initial baseline to compare the performance of other more sophisticated hardware and stimuli designs. The pilot study's results align with the notion that the single-element vibrotactile method cannot effectively convey navigation information. However, this notion was retested with a different haptic stimuli design and a different type of vibration motor while still maintaining the single-element nature in the prototype. This had a profound effect on performance, which will be covered in Chapter 4.

Simultaneously, other modalities with potential were explored. For example, thermotactile stimuli were tested on the back using hot water running through a thin-wall clear plastic tube. The tube could be deformed into simple shapes such as a circle or diagonal line. Issues with the thermotactile method include a slow cooling rate, the lower resolution of the skin to detect subtle temperature changes, and, depending on the body site, the lower resolution of the skin to accurately determine the location of the thermal stimulation, skin adaptability, and the risk of overheating the point of contact on the body (Kappers and Plaisier, 2019). The usual method of thermal stimulation in the published literature uses a Peltier element. However, once heated, the cooling is very slow unless a cooling mechanism is used (Kammermeier et al., 2004). This makes the setup bulky, and hard materials are used. The use of a thin tube instead of a Peltier element allowed a rapid temperature increase by filling it up with hot water, followed by, when required, a rapid temperature decrease by draining the tube empty. This allowed a faster cooling rate without using a bulky hard heat dissipator. However, the other issues mentioned earlier were still observed. In the context of navigation, this method was deemed infeasible for conveying directions and proximity.

Transcutaneous Electrical Nerve Stimulation (TENS) was also considered during this research. This method is commonly used in the field of medicine and prosthetics. The working principle of this method is to pass a pattern of electric current through the skin using electrodes. These electrodes electrically stimulate the mechanoreceptors present in the skin to create tactile sensations. This method was considered for its desirable qualities such as non-moving parts, a thin soft profile, availability, and the cost of the electrodes. Another quality unique to TENS in terms of haptic stimuli design is that it can produce different types of tactile sensations such as pressure, vibration, texture, temperature, and slip (Kajimoto et al., 2003; Pamungkas and Ward, 2016). However, many parameters have to be controlled to consistently create a desired sensation. These parameters include precise control of voltage, current, waveform, electrode size, material, contact force, skin location, thickness, and hydration (Kaczmarek et al., 1991; Kajimoto et al., 2003; Pamungkas and Ward, 2016; Fontana et al., 2018). Moreover, to work with this method, one has to be inducted into a safe, well-equipped laboratory to reduce the risk of generating unpleasant sensations such as pain and, in the worst-case scenario, damaging the receptors in the skin. Whereas these risks are not present with vibrotactile and mechanotactile-based methods. Therefore, during this research, with safety, cost, reproducibility of stimuli, and fewer parameters to manipulate in mind, vibrotactile and mechanotactile methods were further explored.

Vibrotactile devices are mostly based on more than a single vibration motor and are therefore classified as multi-element devices. During the exploratory phase, another prototype was explored through a project called SUITCEYES: a vest consisting of multi-elements distributed over various regions of the torso. Vibrotactile vests offer the advantage of being wearable, hands-free, and can utilise various regions of the torso to deliver complex information. For example, the SUITCEYES vest prototype was used for navigation (Gay et al., 2020) as well as communicating complex information such as semantic content (Darányi et al., 2020; Theil et al., 2020). Similar applications can be found in the published literature (Adebiyi et al., 2017; Ceballos et al., 2018). However, a multi-element vest, in terms of hardware, requires more power and more embedded wiring in the vest, making it prone to breaking. Manufacturing such a vest requires expertise in textile engineering, and creating an adjustable design that fits different shapes and sizes is challenging. Cleaning the vest is difficult, and it must be a snug fit to ensure good contact between the body and the vibrating elements. These factors consequently increase the cost of the vest. In the context of navigation, some of these issues can be mitigated by reducing the scope of the hardware. Therefore, a multi-element vibrotactile belt was introduced to the research.

In the context of navigation, haptic belts have shown to perform well in the published literature (van Erp, 2001; Tsukada and Yasumura, 2004; Erp et al., 2005; Gay et al., 2020). During this research, a haptic belt prototype was chosen for two reasons: firstly, to test the reproducibility of the published results using the given belt prototype and the methodology, and secondly to establish a reliable baseline to compare the performance of any other prototype using the same methodology.

Mechanotactile-based haptic devices were also considered during this research. This method engages the sense of kinesthesia and or proprioception in addition to the cutaneous senses (see section 2.4). This method was considered because the devices based on it have been reported to be intuitive and effective for navigation with minimal training in the published literature (I. Oakley et al., 2006; Spiers et al., 2018; Walker et al., 2018; Rodríguez et al., 2019). These devices rely on moving a body part or applying push/pull forces to the body, and consequently has some disadvantages: bigger sized components, hard material of construction, high weight, grounded, high power requirements, and high cost. Popular devices such as Phantom, Omega series, Geomagic Touch X, Falcon, and similar fall under this category. This research tested three mechanotactile-based prototypes: two joystick-based and a dial-based. These prototypes mitigated some of the aforementioned issues by being handheld but pocket-sized with a lot of room for miniaturisation leading to wearable designs, light weight (100 grams), low in power demands, off-the-shelf, and low in cost, and allowed the testing of active proprioception in the context of navigation. The choice of joysticks was based on personal experience of the researcher that a joystick is a reliable and effective interface that is used to give directions to various types of machines, could they be used in a reverse fashion to seek directions? The choice of the dial was inspired by the feedback from the demonstrations done during the research project.

Finally, in the context of navigation, one attribute that is common among most haptic displays is that they are passive devices (see section 2.5). During this research, the wristband and the belt prototypes were tested as passive vibrotactile devices, while the joysticks and the dial were tested as active proprioceptive vibrotactile devices. This allowed the research project to test the performance of two methods (vibrotactile and proprioceptive vibrotactile) and two modes of interaction (passive and active) using the same methodology.

3.3.2 Passive Vibrotactile Devices

Passive vibrotactile devices can only output information as a vibration, leading to a passive mode of interaction.[8]

Passive vibrotactile prototypes were tested for two reasons: thoroughly evaluating them (locally: sub-research question) and forming a baseline for comparisons (globally: main research question).

Two passive vibrotactile prototypes were evaluated: single-element and multi-element. The single-element passive vibrotactile prototype was in the form of a wristband, whereas the multi-element prototype was in the form of a belt. The following subsections explain each prototype in more detail.

Haptic Wristband

A single-element wristband was chosen to address one of the identified gaps in the existing body of research[9] and function as a baseline device to compare the performance of any other haptic device because it is one of the simplest wearable haptic devices that could be used for navigation and the most fundamental building block of any vibrotactile based device.

The wristband prototype is explained below in terms of hardware and haptic cue design.

In terms of hardware design, as shown in Figure 3.2, the wristband prototype consists of:

a) 2cm wide adjustable hook and loop securing strap.
b) One small piece of Velcro loop fastener stuck to the inside of the strap.
c) 2mm thick cardboard pad with Velcro hook fastener stuck to one of its sides.
d) One ERM vibration motor from Precision Microdrives (Model: 307-103) hot glued to the cardboard pad.

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[8] See Chapter 2; sections: 2.2 stimulation methods, and 2.4 modes of interaction.
[9] See Section 2.6, Identified Gaps in Knowledge

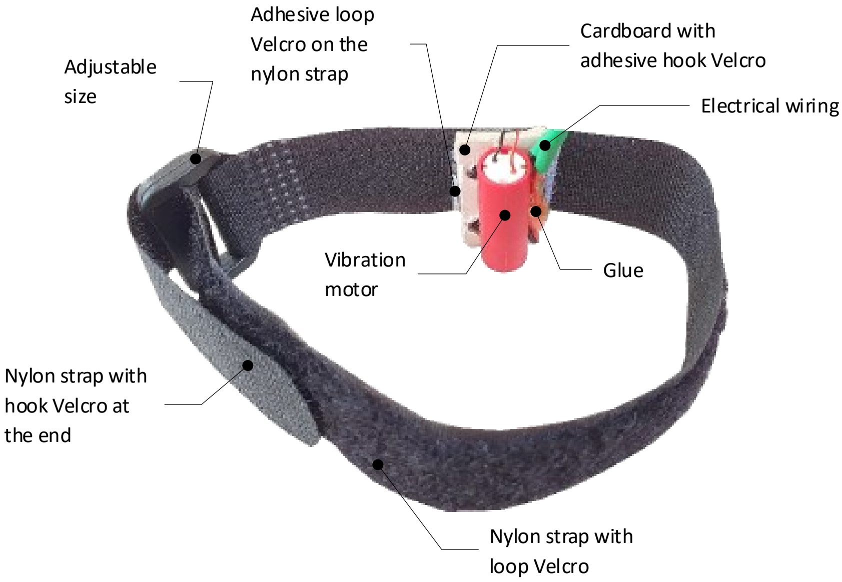


Figure 3.2: Haptic wristband prototype

Regarding haptic cues/stimuli design, each cue represents (haptically) two pieces of information: direction and proximity. Each direction of interest is coupled to a vibration pattern, while proximity is coupled to vibration intensity. For example, the user's "3 o'clock" direction is haptically communicated using a vibration pattern which consists of seven pulses: six vibration pulses are grouped as pairs, and the last pulse is a single pulse. On the other hand, the proximity is haptically communicated by changing the vibration intensity: a stronger intensity to communicate "near" while a weaker one for "far".

Plaisier et al. (2020) studied the technique of grouping(subitising) pulses in the context of numerosity and found it effective for reducing response time, error size, and error rate. This research applies the idea of grouping pulses for numerosity in the context of navigation: a number, which is a count of pulses, represents each direction. For example, the number "1" represents the direction of 9 o'clock, and the number "7" represents the direction of 3 o'clock.

Figure 3.3 shows the haptic stimuli and Table 3.3 lists all possible haptic cues in more detail.

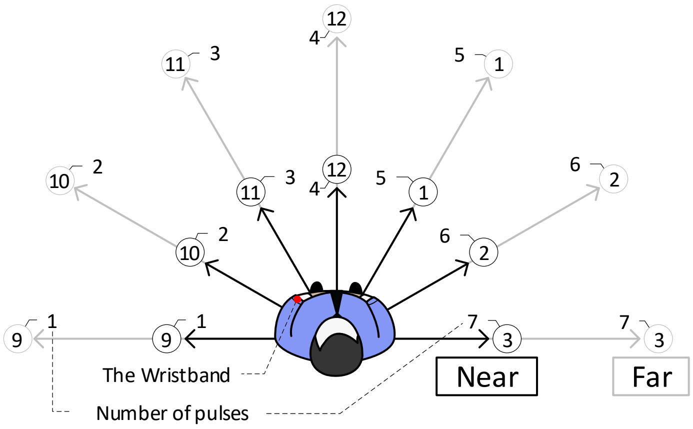
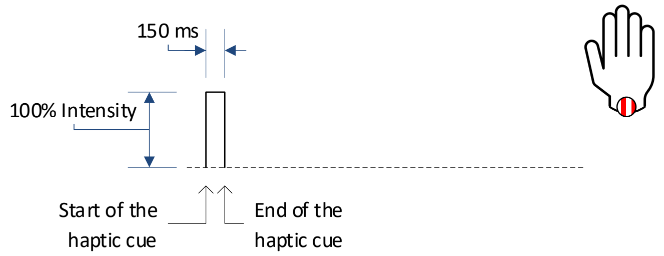
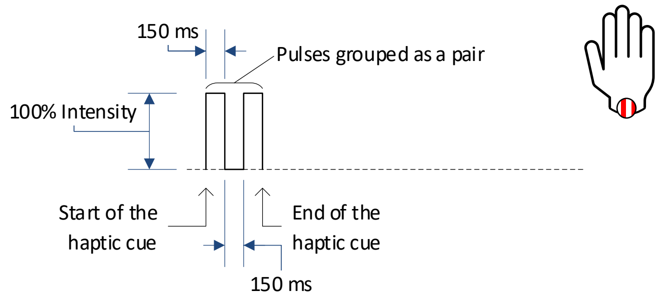
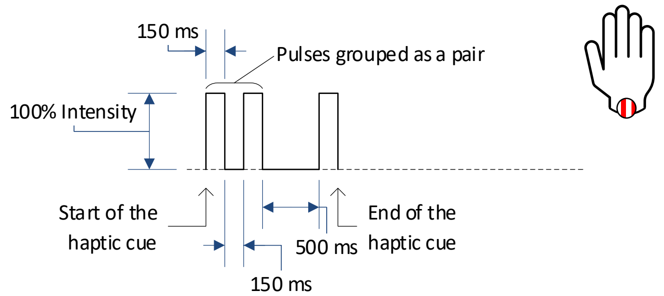
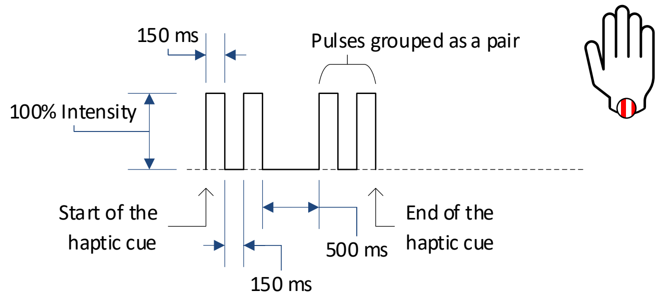
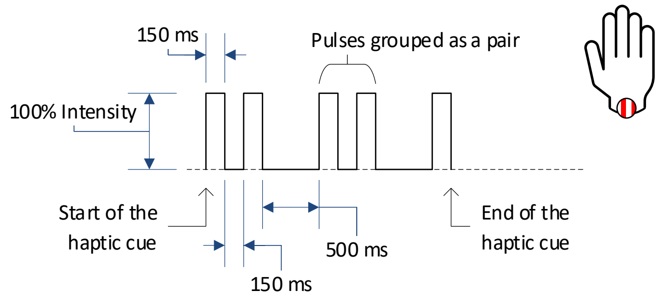
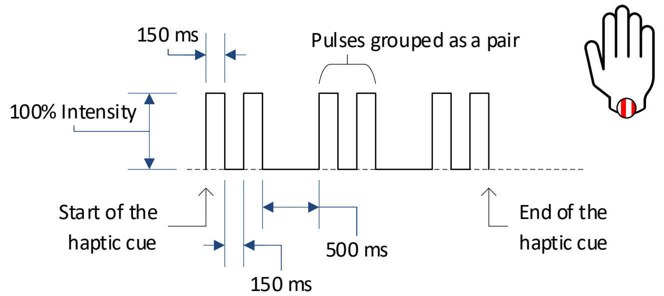
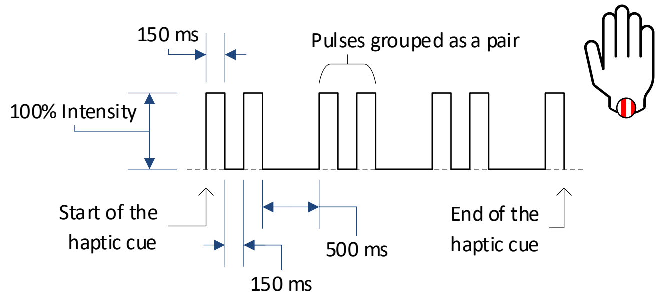
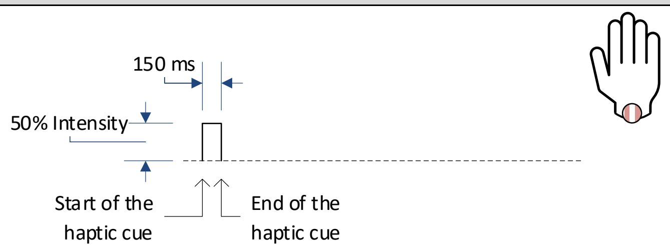
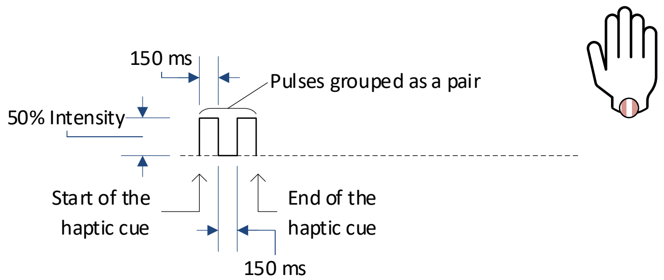
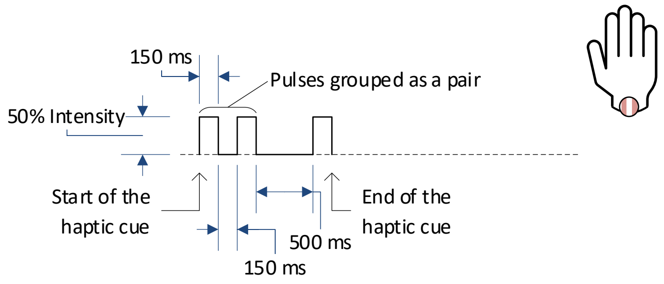
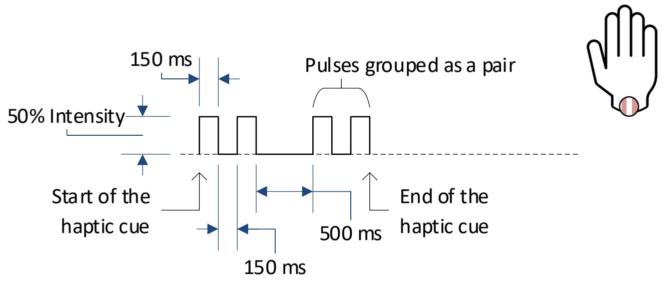
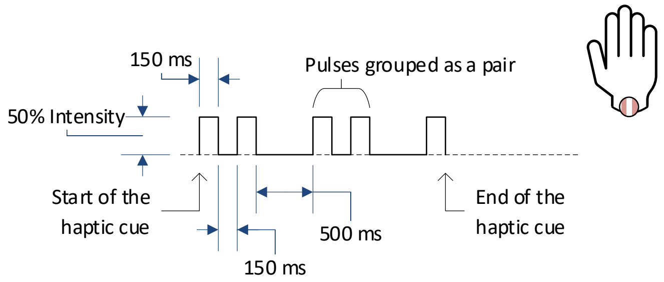
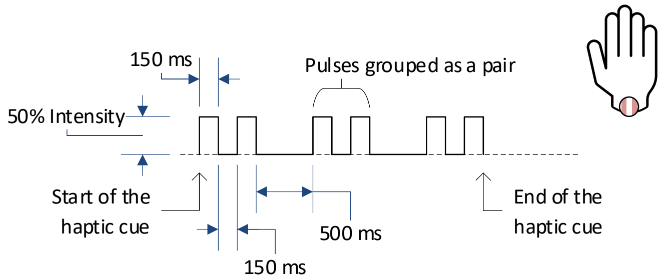
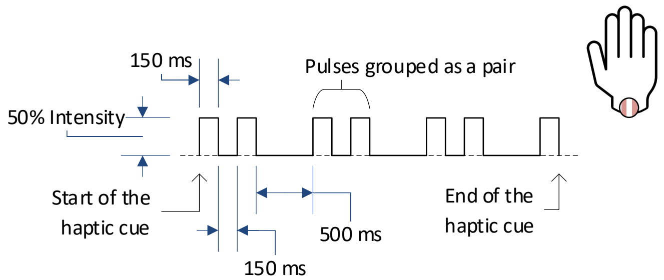


Figure 3.3: Visual representation of the haptic stimuli for the wristband

Table 3.3: Haptic stimuli design details for the wristband

Navigational Information		(Corresponding) Haptic cue
Direction	Proximity	Direction and Proximity
9 o'clock	Near	
10 o'clock		
11 o'clock		

12 o'clock		
1 o'clock		
2 o'clock		
3 o'clock		
9 o'clock	Far	
10 o'clock		

<table>
<tr><td>11 o’clock</td><td></td><td></td></tr>
<tr><td>12 o’clock</td><td></td><td></td></tr>
<tr><td>1 o’clock</td><td></td><td></td></tr>
<tr><td>2 o’clock</td><td></td><td></td></tr>
<tr><td>3 o’clock</td><td></td><td></td></tr>
</table>

Haptic Belt

A multi-element type belt was chosen as another reference to compare the performance of any other haptic device because of its reputation in the existing research studies. It has shown to perform well and to be reliable as a haptic device for navigation.

As explained in section 1.1.2, clock face was chosen as a method to communicate directional information. Clock face has 12 distinct points/hours, each representing a direction. During this research, directions ranging from 9 o'clock, through 12 o'clock, to 3 o'clock, were tested. The haptic belt employed seven vibration motors, each vibration motor representing one of the seven directions. This kind of configuration has been tested by other researchers and has shown to perform well (van Erp, 2001; Tsukada and Yasumura, 2004; Erp et al., 2005).

In terms of hardware design, as shown in Figure 3.4, the belt prototype consists of:

a) 2.5cm wide adjustable nylon black strap with a quick-release buckle.
b) Seven position adjustable custom-made plywood pads with Velcro loop fastener stuck to one of its sides.
c) Seven 2mm thick cardboard pads with Velcro hook fastener, stuck to one of its sides.
d) Seven ERM vibration motors from Precision Microdrives (Model: 307-103) hot glued to cardboard pads.

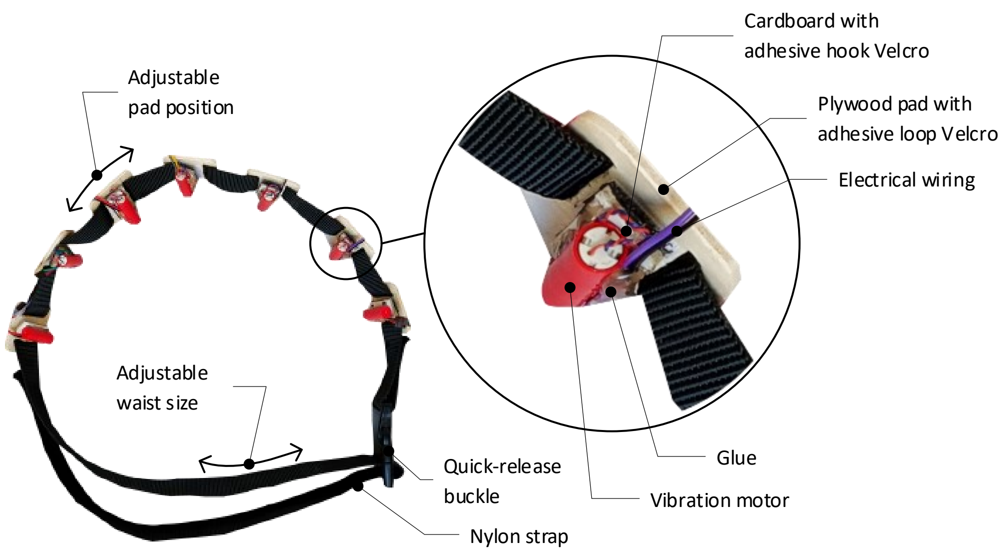


Figure 3.4: Haptic belt prototype

Regarding haptic cues design, cues represent (haptically) two pieces of information: direction and proximity. Each direction of interest is coupled to a vibration motor on the belt, while proximity is coupled to vibration intensity. For example, the user’s “3 o’clock” direction and “near” proximity would be haptically communicated by vibrating the corresponding vibration motor with a stronger intensity compared to the vibration for the “3 o’clock” direction and “far” proximity.

Figure 3.5 shows the haptic stimuli and Table 3.4 lists all possible haptic cues in more detail.

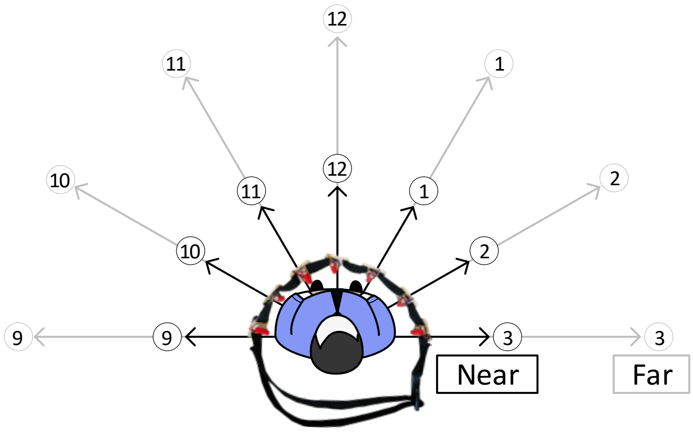
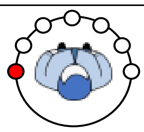
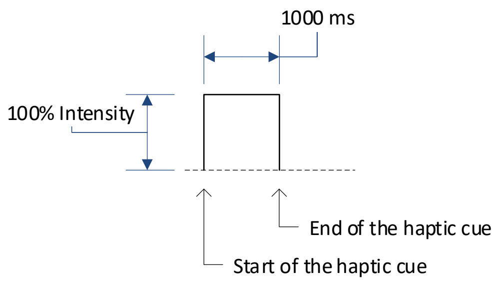
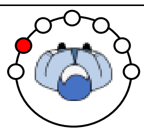
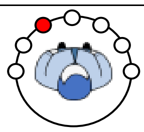
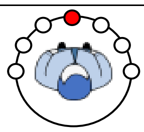
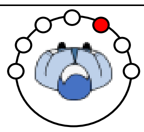
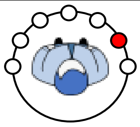
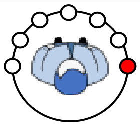
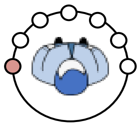
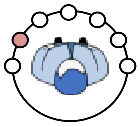
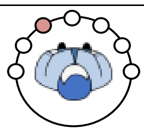
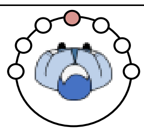
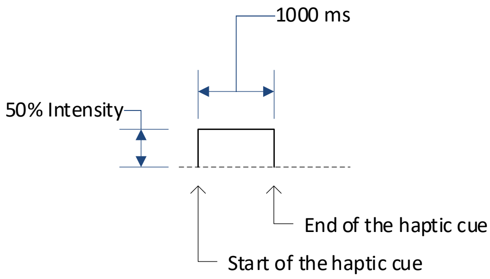
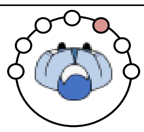
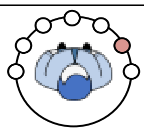
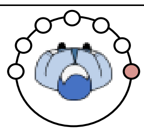


Figure 3.5: Visual representation of the haptic stimuli for the belt

Table 3.4: Haptic stimuli design details for the belt

Navigational Information		(Corresponding) Haptic cue	
Direction	Proximity	Direction	Proximity
9 o’clock	Near		
10 o’clock			
11 o’clock			
12 o’clock			
1 o’clock			

2 o’clock			
3 o’clock			
9 o’clock			
10 o’clock			
11 o’clock			
12 o’clock	Far		
1 o’clock			
2 o’clock			
3 o’clock			

3.3.3 Active Proprioceptive Vibrotactile Devices

Active Proprioceptive vibrotactile devices take the position of one or more body parts as input and output information as a vibration, allowing an active mode of interaction.[10]

Active proprioceptive vibrotactile prototypes were tested for two reasons: thoroughly evaluating them (locally: sub-research question) and comparing them to the passive prototypes (globally: main research question).

[10] See Chapter 2; sections: 2.2 stimulation methods, and 2.4 modes of interaction.

Three active proprioceptive vibrotactile prototypes were evaluated: a single-element joystick with a round rim, a single-element joystick with an octagonal rim, and a single-element dial. As proof-of-concept prototypes, these devices are currently in handheld form. However, if they effectively convey navigational information, the design of the joysticks and the dial can be modified to create wearable versions. For instance, the devices' shape can be optimised to function as accessories that hang on one's belt, or their internal components can be integrated into a wristband. Alternatively, these prototypes could be incorporated into tools that some users may regularly hold, like a white cane, or further miniaturised to be integrated into other commonly worn items, and so on. The following subsections explain each prototype in more detail.

Haptic Joysticks

This research investigates the use of a joystick for navigation to address one of the identified gaps in the existing body of research and to compare the performance to the baseline.[11] Two joysticks were tested: one with a round rim and another with an octagonal rim.

Like other prototypes, both joystick prototypes are explained below in terms of hardware and haptic cue design. In all cases, haptic cues represent two pieces of information: direction and proximity. Each direction of interest is coupled to the position of the stick as an input, while proximity is coupled to a vibration pattern. For example, the user's "3 o'clock" direction is haptically communicated by letting the user move the stick until it is in the correct position. Once in the correct position, the user is alerted using one of the two vibration patterns to indicate proximity. A continuous vibration pattern represents "near", whereas the other pulsating vibration pattern means "far".

Joystick (Round rim)

In terms of hardware design, as shown in Figure 3.6, the joystick (round rim) prototype is a hacked Sony PlayStation Move Navigation Controller, and the key features are:

a) 2-Dimensional (XY) analogue stick guided by a round rim.
b) Handheld, lightweight, ergonomic design with overall external dimensions being Approx. 138 mm × 42 mm (height × diameter).

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[11] See Chapter 2; sections: 2.5 Haptic displays for navigation, and 2.6.4 lack of strict comparisons.

c) One ERM vibration motor from Precision Microdrives (Model: 304-116) hot glued to the inside surface of the body.

Figure 3.6: Haptic joystick (round rim) prototype

Regarding haptic cues, Figure 3.7 shows the haptic stimuli and Figure 3.8 shows an example of a 3 o'clock on the haptic display. Table 3.5 lists all possible haptic cues in more detail.

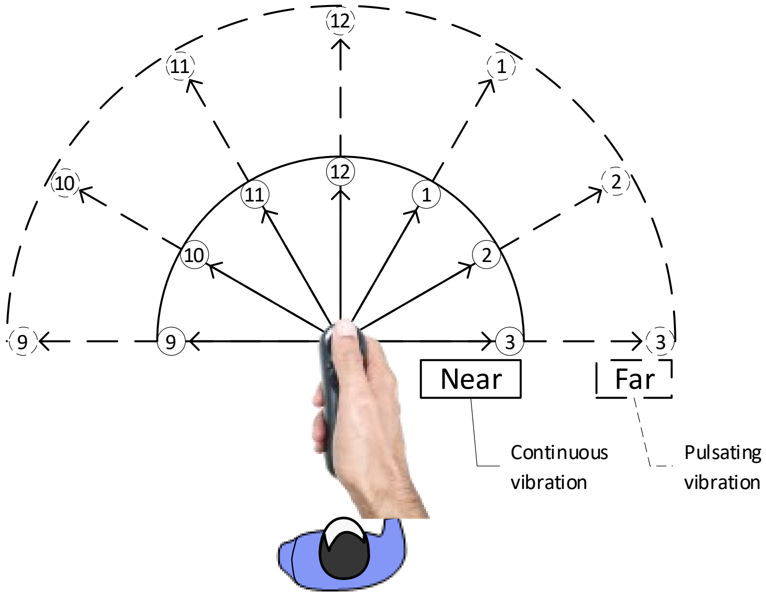


Figure 3.7: Visual representation of the haptic stimuli for the joystick (round rim)

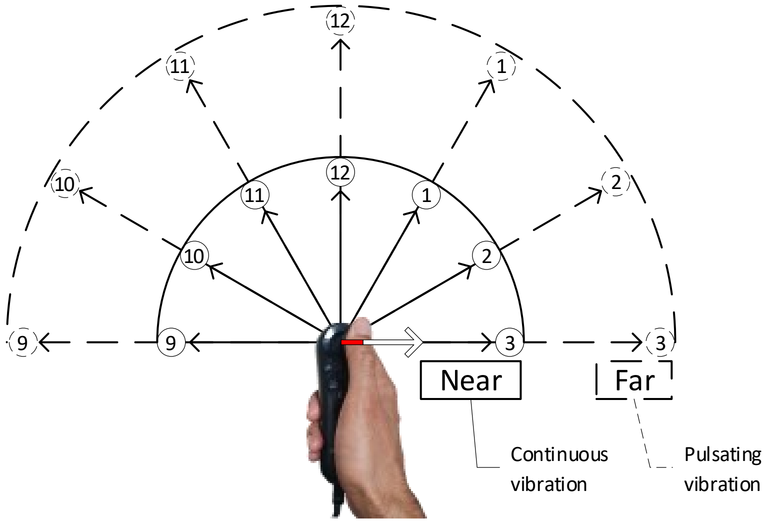
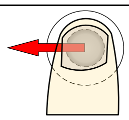
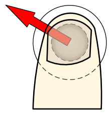
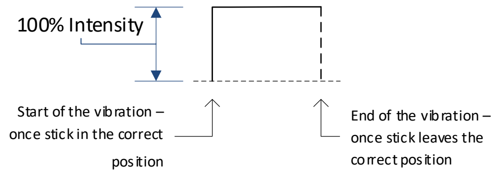
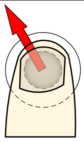
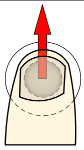
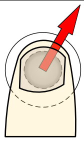
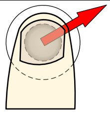
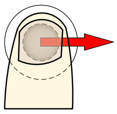
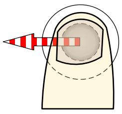
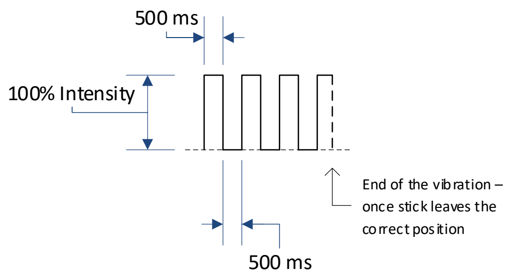
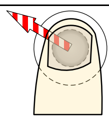
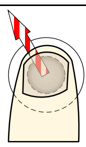
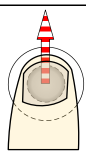
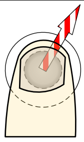
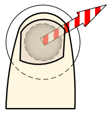
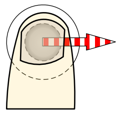


Figure 3.8: Example visual representation of the 3 o'clock direction for the joystick (round rim)

Table 3.5: Haptic stimuli design details for the joystick (round rim)

Navigational Information		(Corresponding) Haptic cue	
Direction	Proximity	Direction	Proximity
9 o'clock	Near		

10 o’clock			
11 o’clock			
12 o’clock			
1 o’clock			
2 o’clock			
3 o’clock			
9 o’clock	Far		
10 o’clock			
11 o’clock			
12 o’clock			
1 o’clock			
2 o’clock			

3 o’clock			

Joystick (Octagonal rim)

In terms of hardware design, as shown in Figure 3.9, the joystick (octagonal rim) prototype is a hacked Nintendo Wii Controller, and the key features are:

a) 2-Dimensional (XY) analogue stick guided by an octagonal rim.
b) Handheld, lightweight, ergonomic design with overall external dimensions being Approx. 110 mm × 50 mm (height × diameter).
c) One ERM vibration motor from Precision Microdrives (Model: 304-116) hot glued to the inside surface of the body.

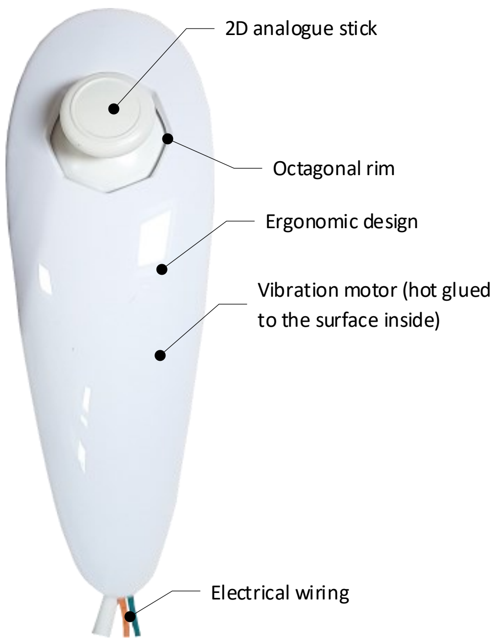


Figure 3.9: Haptic joystick (octagonal rim) prototype

Regarding haptic cues, Figure 3.10 shows the haptic stimuli and Figure 3.11 shows an example of a 3 o’clock on the haptic display. Table 3.6 lists all possible haptic cues in more detail.

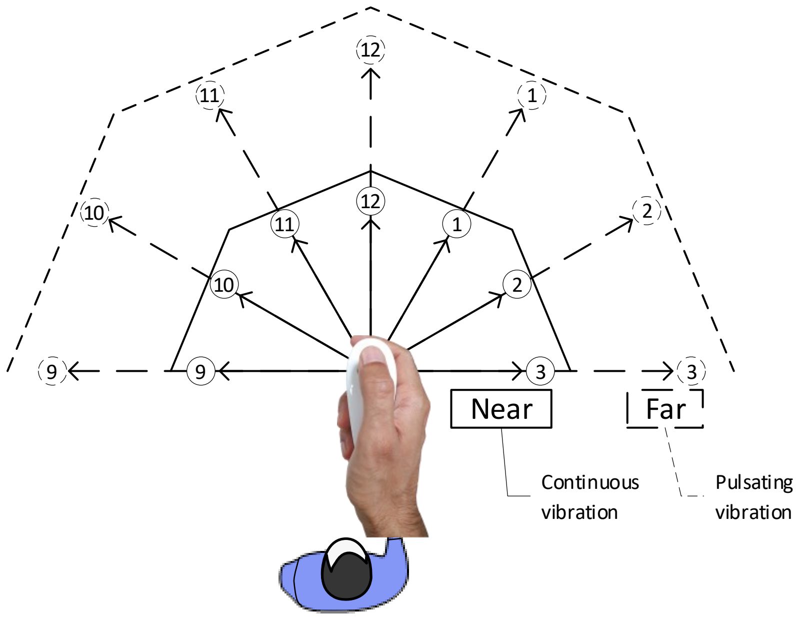


Figure 3.10: Visual representation of the haptic stimuli for the joystick (octagonal rim)

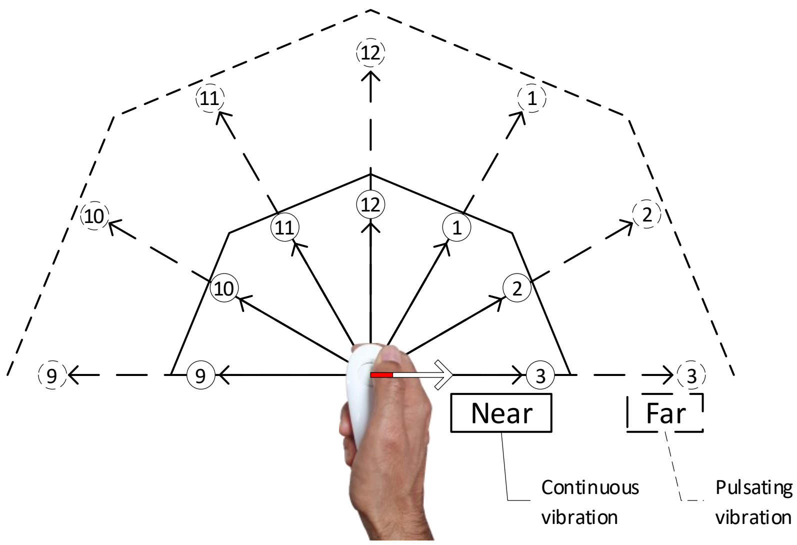
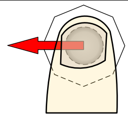
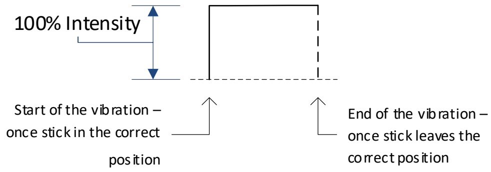
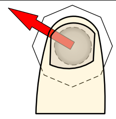
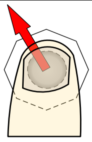
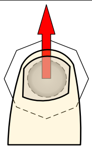
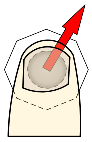
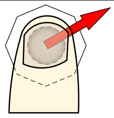
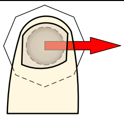
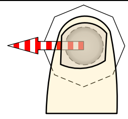
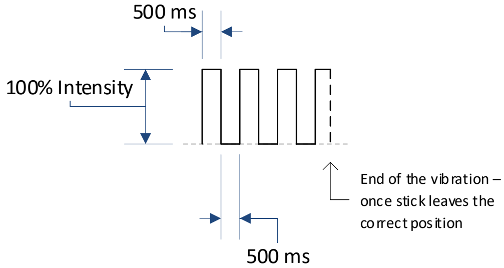
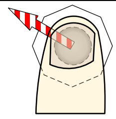
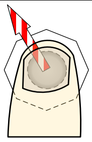
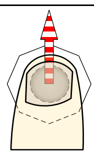
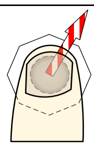
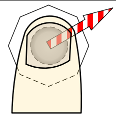
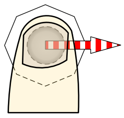


Figure 3.11: Example visual representation of the 3 o'clock direction for the joystick (octagonal rim)

Table 3.6: Haptic stimuli design details for the joystick (octagonal rim)

Navigational Information		(Corresponding) Haptic cue	
Direction	Proximity	Direction	Proximity

9 o'clock	Near		
10 o'clock			
11 o'clock			
12 o'clock			
1 o'clock			
2 o'clock			
3 o'clock			
9 o'clock	Far		
10 o'clock			
11 o'clock			
12 o'clock			
1 o'clock			

2 o’clock			
3 o’clock			

Haptic Dial

In terms of hardware design, as shown in Figure 3.12, the dial prototype uses Nintendo Wii Controller’s body, and the key features are:

a) 24-pulse rotary encoder with 24 indents.
b) Soft-touch knob with an arrow in it.
c) Handheld, lightweight, ergonomic design with overall external dimensions being Approx. 110 mm × 50 mm (height × diameter).
d) One ERM vibration motor from Precision Microdrives (Model: 304-116) hot glued to the inside surface of the body.

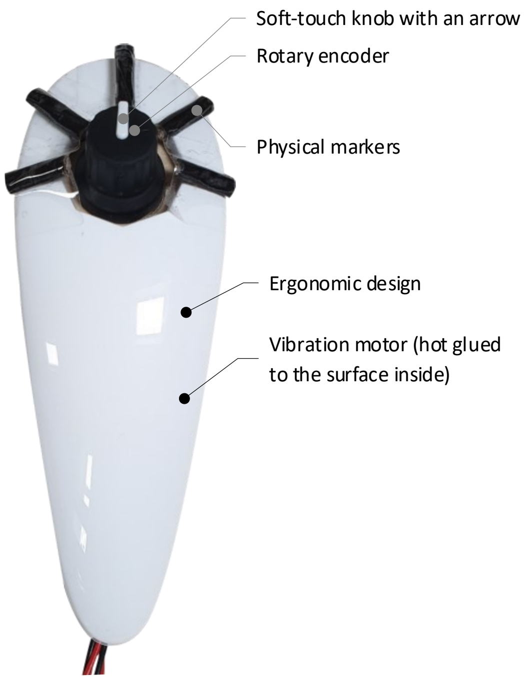


Figure 3.12: Haptic dial prototype

Regarding haptic cues design, like in the case of joysticks, cues represent (haptically) two pieces of information: direction and proximity. However, in the case of the dial, each direction of interest is coupled to a specific position of the rotary knob as an input, while proximity is coupled to a vibration pattern. The rotary knob can be fully and continuously rotated 360 degrees with a click feeling every 15 degrees. Physical markers along the circumference and an arrow in the knob are external features intended to help the user with the task. For example, the "3 o'clock" direction is haptically communicated to the user by letting them rotate the knob until it is in the correct position. Once in the correct position, the user is alerted using one of the two vibration patterns to indicate proximity. A continuous vibration pattern represents "near", whereas the other pulsating vibration pattern means "far".

Figure 3.13 shows the haptic stimuli and Figure 3.14 shows an example of a 3 o'clock on the haptic display. Table 3.7 lists all possible haptic cues in more detail.

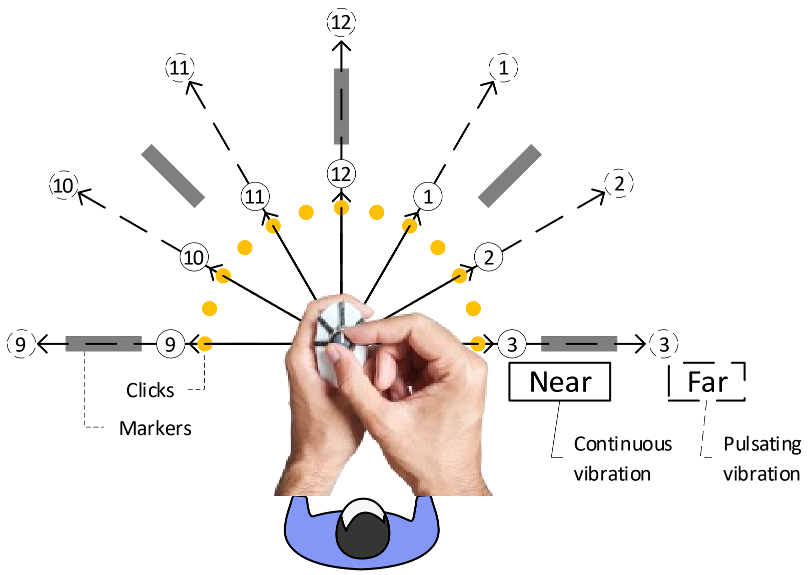


Figure 3.13: Visual representation of the haptic stimuli for the dial

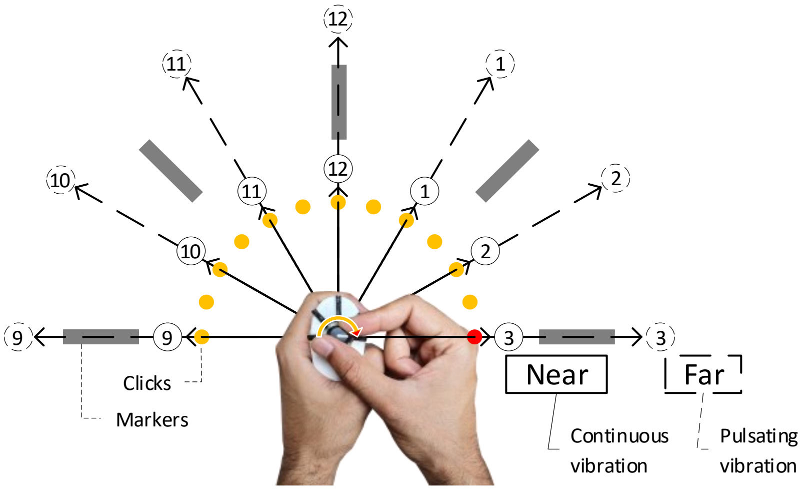
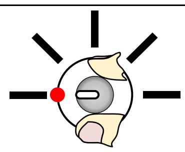
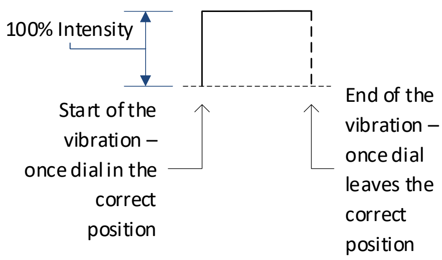
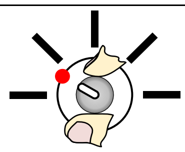
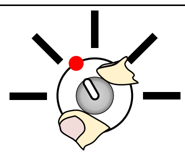
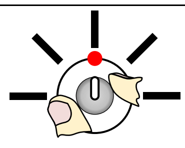
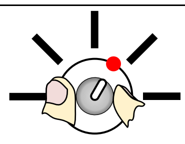
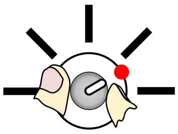
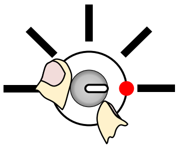
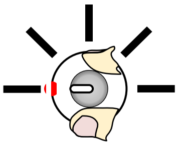
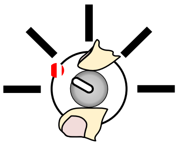
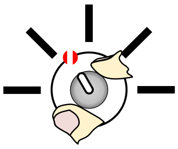
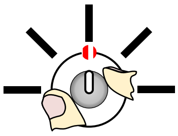
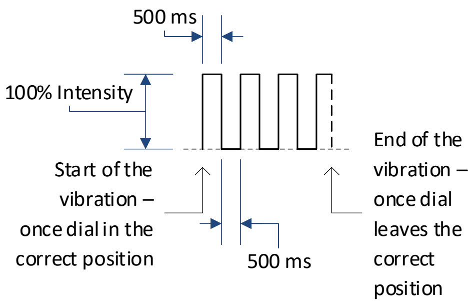
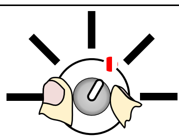
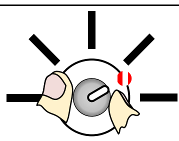
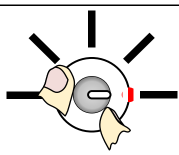


Figure 3.14: Example visual representation of the 3 o'clock direction for the dial

Table 3.7: Haptic stimuli design details for the dial

Navigational Information		(Corresponding) Haptic cue	
Direction	Proximity	Direction	Proximity
9 o'clock	Near		
10 o'clock			
11 o'clock			
12 o'clock			
1 o'clock			

2 o'clock			
3 o'clock			
9 o'clock			
10 o'clock			
11 o'clock			
12 o'clock	Far		
1 o'clock			
2 o'clock			
3 o'clock			

3.4 Task Design

During this research, a session-block-trial model was used. This model is commonly used in human behaviour experiments. According to this model, an experimental task's basic unit is a trial. A trial consists of two parts: stimulus and (participant's) response. A group of trials is called a block. A single iteration of one or more blocks with a participant forms a session. The session-block-trial model allows researchers to control and manipulate experimental variables systematically, observe participant behaviour across multiple trials and blocks, and analyse the data collected for statistical analysis and interpretation. It helps to provide a structured framework for investigating and understanding human behaviour in a controlled laboratory setting. Using a standardised approach such as a session-block-trial model can also help with replicating studies because it allows the definition and communication of an experimental design without ambiguity. Moreover, tools developed by the research community exist based on such standardised approaches. For example, during this research, a Unity-based tool (UXF) was employed, which had been developed by another researcher (Brookes et al., 2019).

During any given trial, the task for the participant was to experience one of the haptic stimuli and report the perceived navigational information. Each haptic stimulus represented a direction and proximity. Seven clock-face directions and two proximity labels were used to form fourteen unique haptic stimuli as represented in Figure 3.15.

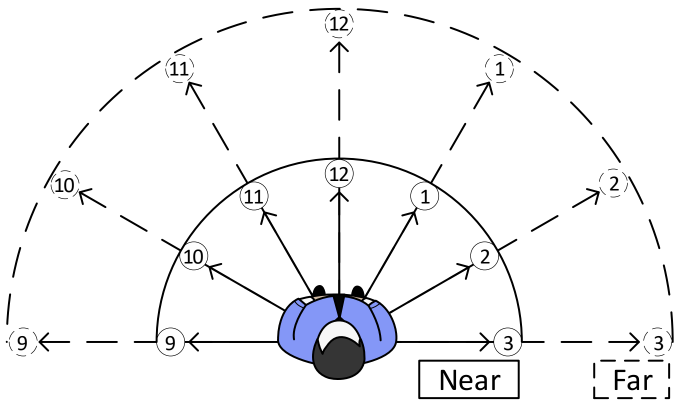


Figure 3.15: Representation of directions of interest and proximities

As shown in Figure 3.16, the stimuli were divided into two groups: near and far, each group contained seven stimuli. Two blocks of trials were formed: near-only (block1) and near-and-far (block2). Block1 of trials contained stimuli from the near group, while block2 contained stimuli from the near and far group. Each stimulus was repeated four times in each block.

The session was divided into two parts/scenarios: direction-only (part1) and direction-and-proximity (part2). During part1 of the session, participants experienced trials from block1 and were asked to verbally report only the perceived direction, while during part2, they were asked to report both the perceived direction and proximity.

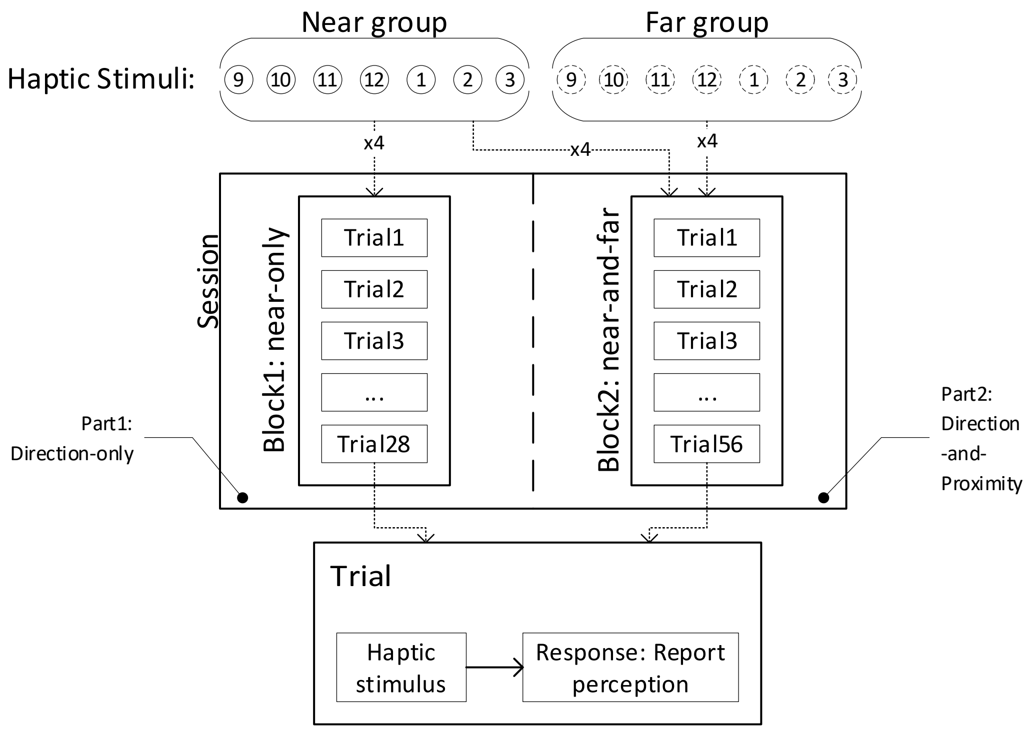


Figure 3.16: Overview of the session-block-trial setup

3.5 Data Collection

Data collected can be divided into three categories:

- **Participant data** was collected for three variables of interest:
  - Age,
  - Gender
  - Handedness
- **Performance data** were collected for five variables of interest:

  Objective measures

  - User response
  - Time-taken
  - Repeats-taken

  Subjective measures

  - Experienced workload
  - Usability

- **Interview data** were collected as notes during an informal interview at the end of each session

A description of each variable of interest and the method of data collection used is given below.

Age, Gender (male or female), and Handedness (left or right-handed) information were collected by verbally asking each participant at the beginning of their first session.

User response was verbally reported during each trial and recorded manually through Unity by the researcher.

Time-taken is the duration of a given trial. It was recorded automatically in Unity.

Repeats-taken is the number of times a stimulus was haptically shown during a given trial before the participant gave their response. It was recorded automatically in Unity. The first exposure of the given stimulus was not counted as a repeat.

The experienced workload resulting from performing the task with a given prototype was measured using a well-established method introduced by NASA called Task Load Index (TLX). The paper-based questionnaire was given at the end of each part of the session.

The usability of a given prototype to perform the task was measured using another well-established method introduced by Systems Digital called System Usability Scale (SUS). The paper-based questionnaire was given at the end of each part of the session.

Performance data for objective measures were collected through Unity (Unity Technologies, 2022) during the tests. An open-source Unity library called Unity Experiment Framework (UXF) was used in Unity to administer tests and collect data in a structured manner (Brookes et al., 2019). Data for subjective measures were collected through paper-based questionnaires at the end of the two parts of the session. The objective variables' performance has been termed the effectiveness of a given prototype in performing the task, while the subjective variables' performance has been termed the intuitiveness of a given prototype in performing the task. An overview of the data collection is represented in Figure 3.17.

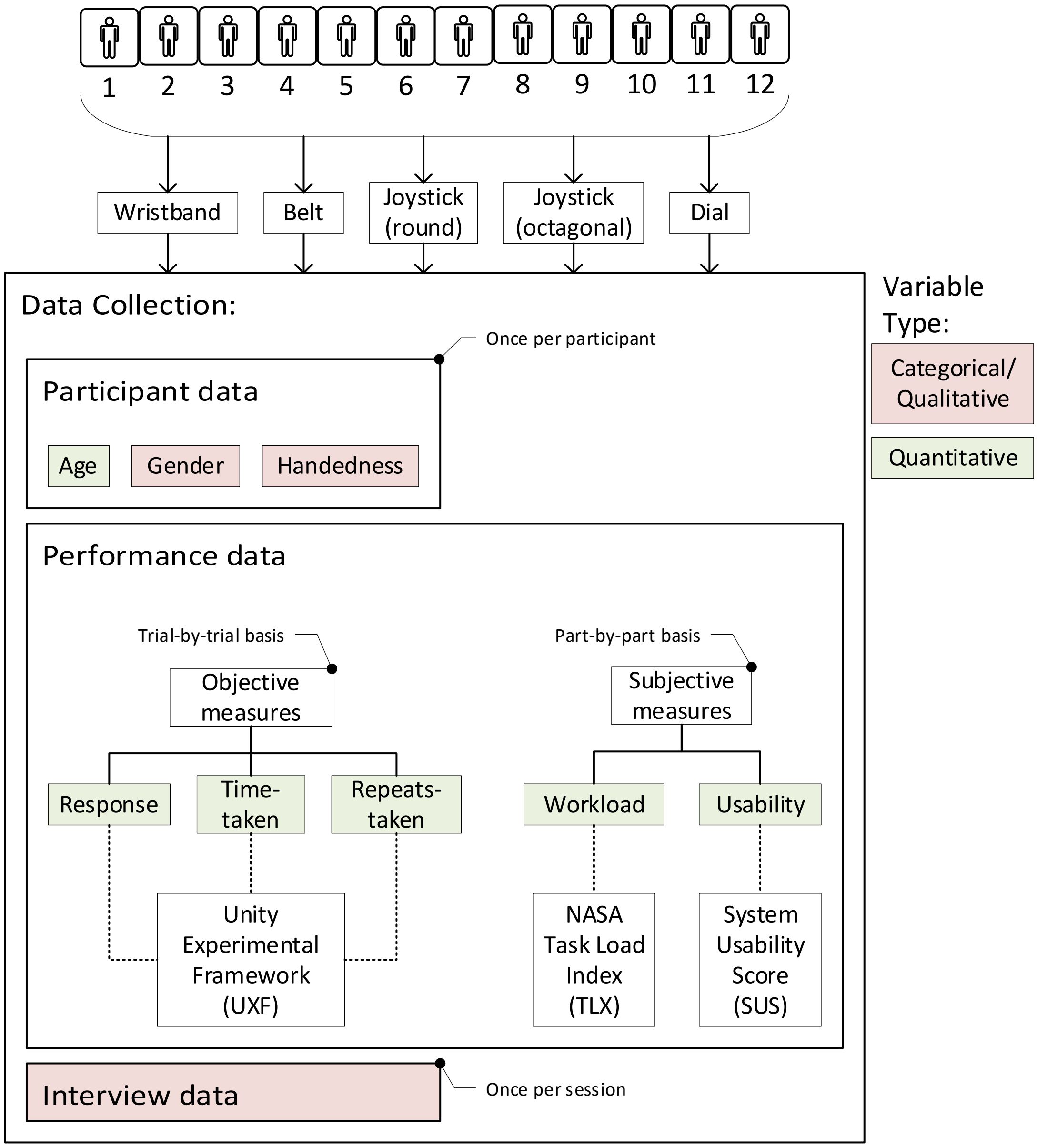


Figure 3.17: Overview of the data collection

3.6 Experimental Procedure

Twelve participants used five prototypes each to perform the same task, which resulted in sixty sessions. Any given participant was allowed to do only one session per day; on average, bookings were such that there was a weeklong gap between two sessions for a given participant. Each session followed the same routine:

- **Session Commencement**

  The session was started once the participant had taken a seat and was ready.
- **Participant Briefing**

The participant was briefed about the experiment; a copy of the information sheet was provided, which covered the following:

- Purpose of the project.
- Overview of the experiment, including the structure of the session and the prototype to be used during that session.
- Risks of taking part in the experiment.
- Benefits of taking part.
- Confidentiality.
- Data collection.
- Data publishment.
- Research team's contact details.

- **Consent Form**

  The participant was asked to read and sign the consent form, which covered the following:

  - They understand the information given to them earlier during the briefing.
  - Participation is voluntary.
  - Anonymisation of data collected.
  - Confidentiality of the information.
  - Usage of the anonymised data collected.
  - Storage of the data collected.
  - They will update the research team if there is a change of mind about participation.
  - Permission to keep a record of their contact details for future participation.

- **Part 1: Direction-Only Condition**

  Part1 (direction-only) of the session was started, which included the following steps:

  - Participant's age, gender, and handedness were noted.
  - The prototype for the session was revealed.
  - A practice run (a practice block of seven trials) was done, which was an exposure to each near-stimulus once.
  - The workload and usability questionnaires were explained.
  - The participant was instructed to wear a blindfold and earmuffs. This was done to reduce the interference of sight and sounds
  - Block1 of trials (near-only) was done. During each trial, the participant verbally reported their response, which ended the current trial, and the next trial began.
  - After the last trial, the participant was instructed to remove the blindfold and earmuffs.

  - The participant was instructed to complete the workload questionnaire. They were encouraged to ask for clarification or explanation if needed.
  - The participant was instructed to complete the usability questionnaire. They were encouraged to ask for clarification or explanation if needed.
- **Intermission**

  A break of (up to) fifteen minutes was given.
- **Part 2: Direction-and-Proximity Condition**

  Part2 (direction-and-proximity) of the session was started, which included the following steps:
  - A practice run (a practice block of fourteen trials) was done, which was an exposure to each near and far stimulus once.
  - The workload and usability questionnaires were given a quick recap.
  - The participant was instructed to wear a blindfold and earmuffs. This was done to reduce the interference of sight and sounds
  - Block2 of trials (near-and-far) was done. During each trial, the participant verbally reported their response, which ended the current trial, and the next trial began.
  - After the last trial, the participant was instructed to remove the blindfold and earmuffs.
  - The participant was instructed to complete the workload questionnaire. They were encouraged to ask for clarification or explanation if needed.
  - The participant was instructed to complete the usability questionnaire. They were encouraged to ask for clarification or explanation if needed.
- **Informal Interview**

  An informal interview was done in order to collect the participant's experience-based comments. Below are a few examples of the questions that the participants were asked:
  - How did they find intensity change to represent proximity? If applicable to the prototype that had been tested that session.
  - How did they find pulsation to represent proximity? If applicable to the prototype that had been tested during that session.
  - What would they change about the prototype?
  - What did they like about the prototype?
  - What did they dislike about the prototype?
  - Was there any direction(s) that was easier than the others?

- Was there any direction(s) that was harder than the others?
- How would they rank the prototypes so far tested?
- Which mode would be their preference: active or passive?
- What did they think about the questionnaires?

- **Session Conclusion**

  Finally, the session was concluded with a note of gratitude.

The overview of the experimental procedure is represented in Figure 3.18.

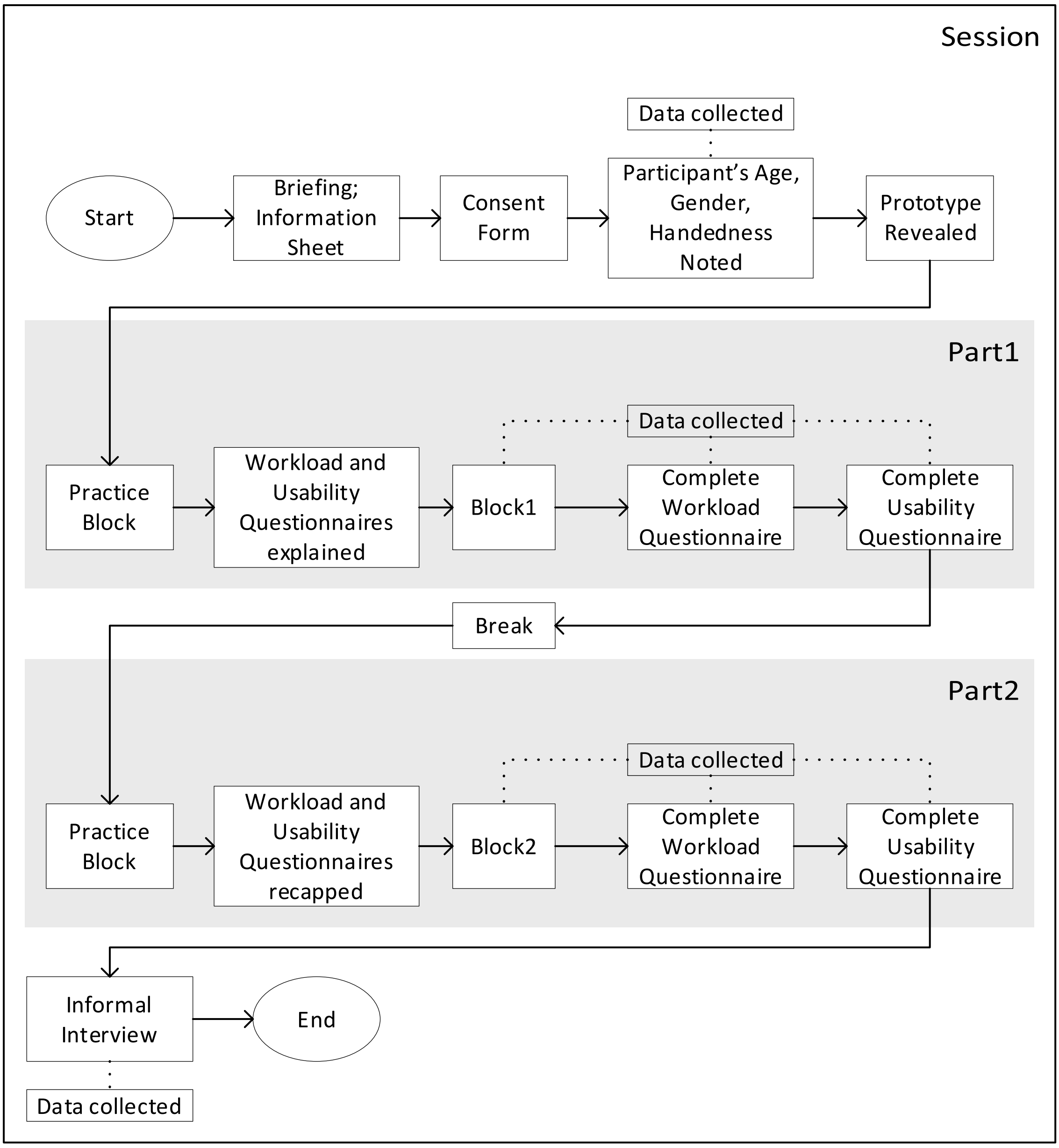


Figure 3.18: Overview of the experimental procedure

3.7 Data Analysis

The Data Analysis section explains how the collected information was transformed into meaningful insights. This section is divided into two sub-sections: Data Preparation and Statistical Analysis.

3.7.1 Data Preparation

Data collected (see section 3.5) can be categorised into three categories: participant, performance, and interview data.

Participant data was collected at the beginning of the session and included age, gender, and handedness. This information was collected through UXF interface and stored in a comma-separated values (CSV) file.

Performance data was collected through Unity using a tool called Unity Experiment Framework (UXF) as well as pen and paper-based questionnaires. Performance data collected can be further categorised as objective and subjective performance related. Objective performance related data included user response to each stimulus, time taken to respond, number of times a given stimulus was repeated (before responding with an answer). Subjective performance related data included numerical ratings for experienced mental workload as well as Likert-scale ratings for perceived usability of the prototypes. The data collected was stored in a CSV file. Individual CSV files for each participant and each session were combined into a mater CSV file. The master CSV file was then analysed using Python based libraries such as NumPy, Pandas, Matplotlib, SciPy etc.

Interview data was collected through informal interviews at the end of each session. Below are examples of the questions that the participants were asked:

- How did they find intensity change to represent proximity? If applicable to the prototype that had been tested that session.
- How did they find pulsation to represent proximity? If applicable to the prototype that had been tested during that session.
- What would they change about the prototype?
- What did they like about the prototype?
- What did they dislike about the prototype?
- Was there any direction(s) that was easier than the others?
- Was there any direction(s) that was harder than the others?
- How would they rank the prototypes so far tested?
- Which mode would be their preference: active or passive?
- What did they think about the questionnaires?

Participant comments were noted by the researcher in a word file. Relevant information was captured as notes. These notes were then data coded in excel and manual content analysis was done, for example, by counting number of times a prototype was ranked as first choice, recurring features liked or disliked, and so on.

3.7.2 Statistical Analysis

This section outlines the methods employed to analyse the data obtained from the experimental sessions, illustrating how statistical tools have been used to discern the effects of various haptic prototypes on participants' performance. This section provides details on the data preparation, selection of tests, criteria for statistical significance, and effect size calculations, providing a transparent view of the analytical process that informs the subsequent interpretations and discussions of the findings.

Data collected for each variable of interest was statistically analysed using descriptive statistics as well as inferential statistics. Descriptive statistics such as mean, proportions, and standard deviation for the key variables were used to summarise and understand the data. Whereas inferential statistics was used to make confidence intervals, perform t-tests, and perform Analysis of Variance (ANOVA) tests.

Age was summarised as a sample mean with standard deviation.

Gender (male or female) was summarised as a sample proportion.

Handedness (left or right-handed) was summarised as a sample proportion.

User response was converted into Accuracy rate and then summarised as a sample mean accuracy (as a percentage) for a given prototype during Part1 and Part2 of the session. Furthermore, 95% confidence intervals were calculated and plotted using a bar plot function from a Python-based library called Seaborn.

Time-taken is the duration of a given trial. Data for this variable was summarised as the mean amount of time taken in seconds per trial for a given prototype during Part1 and Part2 of the session. Furthermore, 95% confidence intervals were calculated and plotted using a bar plot function from a Python-based library called Seaborn.

Repeats-taken is the number of times a stimulus was haptically shown during a given trial before the participant gave their response. The first exposure of the given stimulus is not counted as a repeat. Data for this variable was summarised as a sample mean of the number of repeats taken per trial for a given prototype during Part1 and Part2 of the session. Furthermore, 95% confidence intervals were calculated and plotted using a bar plot function from a Python-based library called Seaborn.

The experienced workload resulting from performing the task with a given prototype was measured using a well-established method introduced by NASA called Task Load Index (TLX). The paper-based questionnaire was given at the end of each part of the session. The questionnaire requires users to rate their experience at the end of each part on six subscales: Mental Demand (MD), Physical Demand (PD), Temporal Demand (TD), Performance (P), Effort (E), and Frustration (F). Followed by fifteen pair-wise comparisons to add weighting to each rating. And finally, from weighted ratings an overall experienced workload score is calculated for each participant for each part of the session and for each prototype used. The scores were summarised as a sample mean of the overall workload experienced by each participant for a given prototype during part1 and part2 of the session. Furthermore, 95% confidence intervals were calculated and plotted using a bar plot function from a Python-based library called Seaborn.

The usability of a given prototype to perform the task was measured using another well-established method introduced by Systems Digital called System Usability Scale (SUS). The paper-based questionnaire was given at the end of each part of the session. The questionnaire requires users to rate the prototype used against ten questions on a five-point scale ranging from “strongly agree” to “strongly disagree”. The ratings are used to calculate the system usability score for each participant for each part of the session and for each prototype used. The scores were summarised as a sample mean of usability score perceived by each participant for a given prototype during part1 and part2 of the session. Furthermore, 95% confidence intervals were calculated and plotted using a bar plot function from a Python-based library called Seaborn.

In addition to the summary statistics, the data for each performance-related variable was tested using a series of Analysis of Variance (ANOVA) tests. This was done to confirm statistically significant difference for a given variable across the five prototypes. Followed by a series of Tukey’s Honestly Significant Difference tests as post-hoc tests. This was done to exactly see which prototypes significantly differed among all possible pairwise comparisons. Results from these tests were used to address the sub-research questions and the main research question of this research. An overview of the data analysis is represented in .

Alpha Criterion

The researcher adopted a significance level of 5% (alpha value of 0.05) consistently throughout t-tests, ANOVA tests, and Tukey’s Honestly Significant Difference (HSD) post-hoc tests. Several considerations informed this choice: adherence to the convention within the field (Chen et al., 2018; Buimer et al., 2018; Mazella et al., 2018; Spiers et al., 2023), a pragmatic assessment that the practical impact of committing a type-1 error is less critical at this stage compared to a type-2 error. The rationale is grounded in the understanding that a type-1 error is more likely to be identified in subsequent replication studies, while a type-2 error could prematurely lead to dismissing the proposed method (i.e., active proprioception-based haptics for navigation). Given the relatively modest sample size (n=12), which inherently yields lower study power and increases the risk of type-2 error, opting for a more stringent alpha value would exacerbate the likelihood of this undesirable error. Lastly, the decision to use the conventional alpha value is influenced by the absence of substantial prior research evidence either favouring or opposing the method under examination.

Effect Size

An effect size is a quantitative measure that describes the strength or magnitude of a relationship or the size of the difference between two groups in a statistical study. It provides additional information beyond statistical significance and helps researchers understand the practical or substantive importance of their findings.

While statistical significance (p-value) indicates whether an observed effect is likely to be due to chance, effect size quantifies the magnitude of the observed effect. Both are important in the interpretation of study results, and a combination of significance testing and effect size reporting provides a more complete understanding of the practical implications of research findings.

Therefore, during this research, both significance p-value as well as effect size were reported. Effect sizes are reported as both standardised (Cohen’s d or dz) as well as unstandardised (as mean difference in the original units of measurement). Effect size as Cohen’s dz is reported for with-subjects differences between direction-only (part 1) and direction-and-proximity (part 2) parts. For example, for a given variable of interest (accuracy) and haptic prototype (haptic wristband) the mean difference between part 1 and part 2 was reported as a percentage as well as the standardised effect size as Cohen's dz. However, effect size as Cohen's d is reported for between-subjects difference between two prototype's performance for a given variable of interest (e.g., accuracy) and scenario (e.g., direction-only). For example, for a given variable of interest (accuracy) and scenario (direction-only) the mean difference between haptic belt's performance and haptic wristband's performance was reported as a percentage as well as the standardised effect size as Cohen's d. (Lakens, 2013)

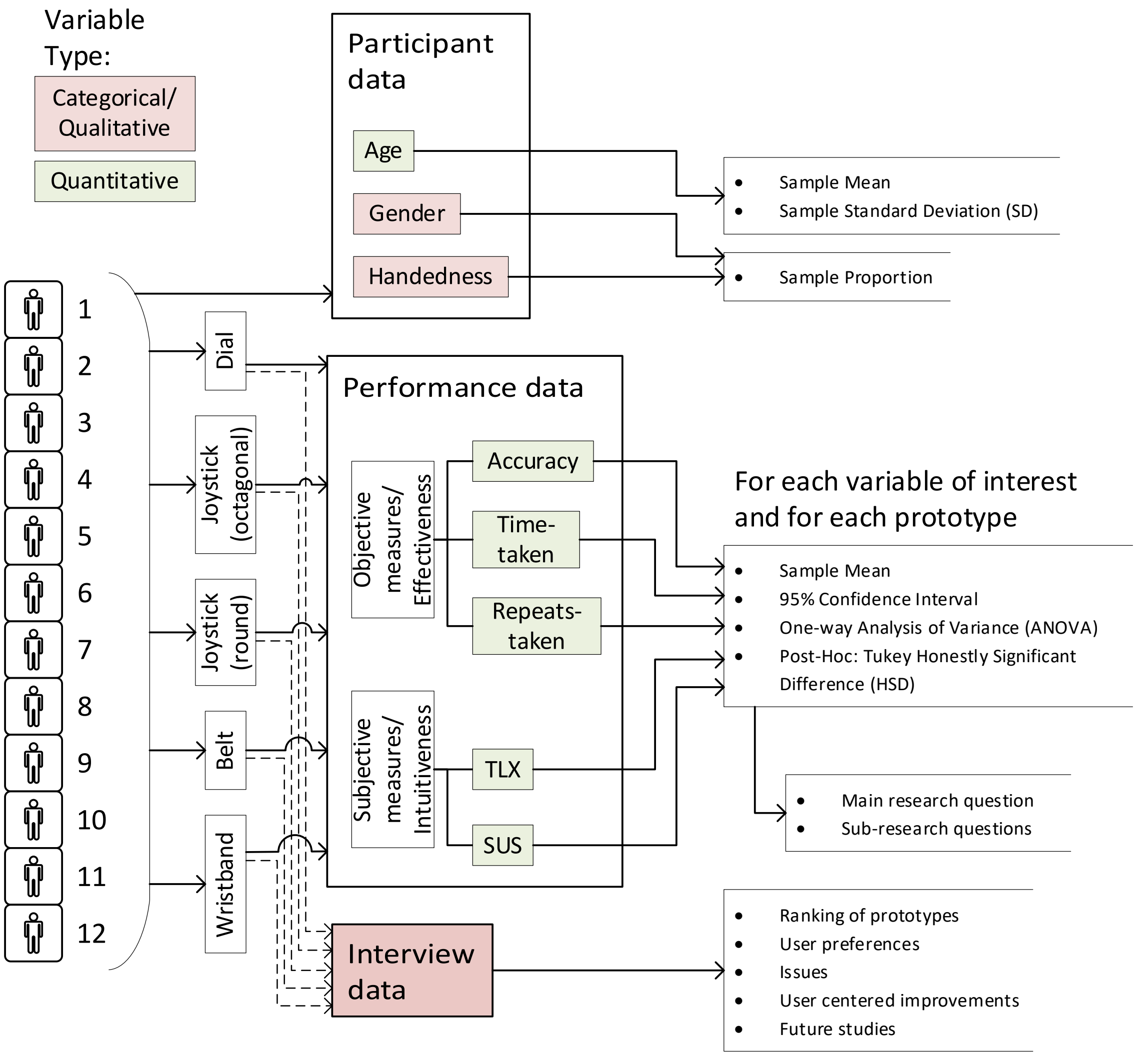


Figure 3.19: Overview of the data analysis

3.8 Conclusion

The methodology above allowed the collection and analysis of subjective and objective data from a pool of twelve participants, where each participant, over five sessions, used five unique prototypes to perform the defined navigation tasks. Data collection and analysis were done to address two sub-research questions (results covered in Chapter4 & 5) and one main research question (results covered in Chapter6). An overview of the methodology is represented in Figure 3.1.

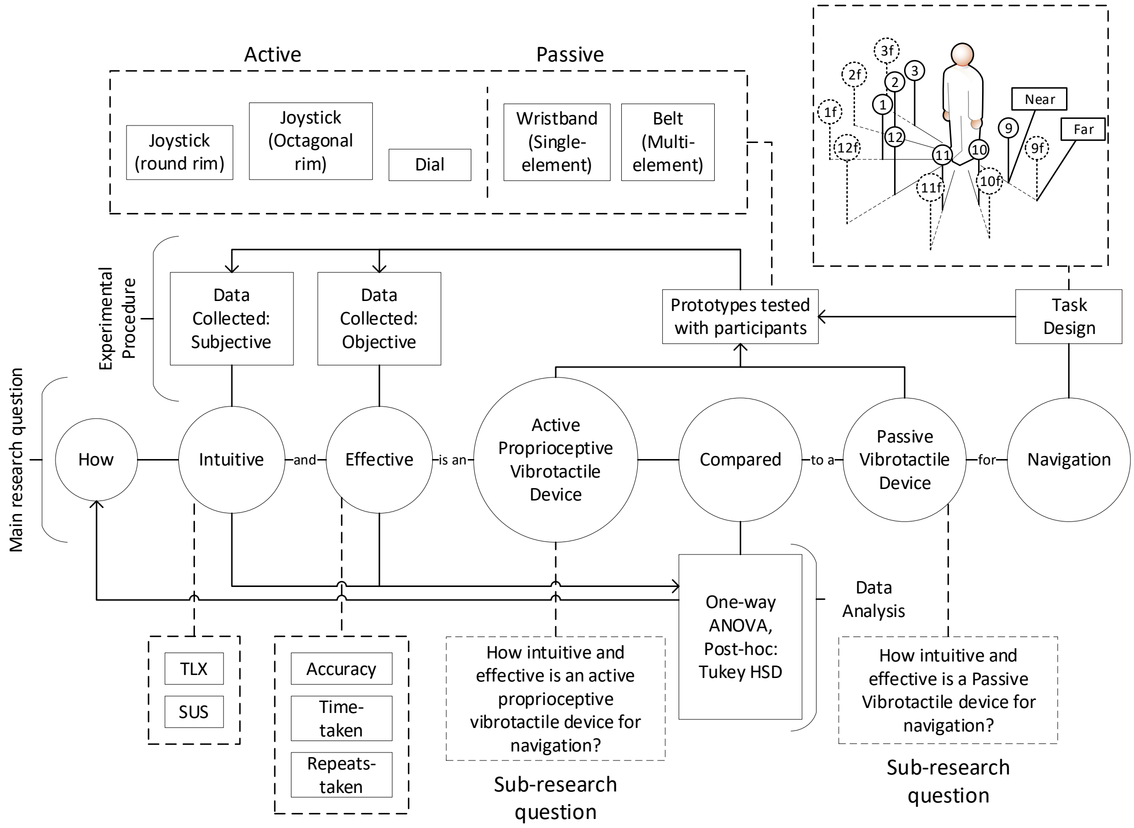


Figure 3.1: Overview of the methodology, its components, and the main research question

Chapter 4
Passive Vibrotactile Devices: Performance of Receiving Direction and Proximity

This chapter evaluates the performance (intuitiveness and effectiveness) of the two passive vibrotactile devices as navigational haptic displays: a haptic belt (multi-elements) and a haptic wristband (single-element). The reason for choosing a haptic belt is its popularity in academia for navigational tasks, whereas, for a haptic wristband, the reason is its basic, simple, wearable single-element design. Another reason for choosing a single-element haptic wristband is to verify its performance compared to a multi-element display (the haptic belt).

This chapter has four main sections, one for each passive vibrotactile device, one for comparing the two devices across two parts (direction-only part1 and direction-and-proximity part2), and the last for presenting the qualitative findings which are based on the informal interviews. First three sections cover details of the experimental setup, present and discuss results, and compare the performance of the given device across two parts locally. Whereas the last section lists interesting comments, issues, and improvement suggestions made by the participants for each of the devices.

4.1 The Haptic Belt

Researchers have repeatedly tested haptic belts for various applications: for example, as an aid for machine control (Erp et al., 2005), alerting device(Wang et al., 2016), general and assistive navigation where visual or auditory cues are obstructed or unavailable (Tsukada and Yasumura, 2004), speech comprehension (Reed et al., 2018), and non-verbal social communication (Ceballos et al., 2018). Its popularity is based on good accuracy rates, minimal training, and low-cost wearable form. One disadvantage of vibrotactile devices, including the belt, is the rapid adaptability of the cutaneous receptors.

The existing evaluations of the haptic belts, in a navigational context, have been based on objective measures, such as accuracy and time taken. In contrast, subjective measures, such as the experienced mental workload and perceived usability, are left unaccounted for during these evaluations. This narrow objective method of evaluation prevents a deeper understanding of the user experience of the haptic device for a task (Jahedi and Méndez, 2014). This understanding, by having both types of measurements, will allow better user-centred design iterations aimed at improving haptic displays for navigation. A thorough evaluation of navigational haptic devices is a gap in the literature, as explained in Chapter 2.

The subsections below present the experimental setup used to collect data for the objective and subjective measures of the haptic belt. It also presents the results as graphs for each variable of interest, accompanied by a discussion where needed.

4.1.1 Experimental Setup

This subsection describes the experimental setup used for testing the haptic belt. The experimental setup is explained in terms of four aspects: participants, apparatus, stimuli, and task. The explanation should allow replication of the experimental setup.

Participants

Twelve sighted individuals, aged between 23 and 59, tested the haptic belt. All participants were right-handed, six males and six females, with a median age of 33 and a mean age of 39 ± nine years of standard deviation.

As mentioned in chapter3, the same twelve participants tested each of the five prototypes over five sessions. Sessions for a given participant were separated by a significant amount of time. The testing order of prototypes was counterbalanced across participants to avoid learning effects as much as possible. The exact session numbers for the haptic belt's testing are summarised in Table 4.1.

Table 4.1: Participants' session numbers for haptic belt tests

Participant	Session no.
P1, P2	4th
P3, P4	5th
P5, P6	1st
P7, P8	1st
P9, P10	5th
P11, P12	2nd

Apparatus

Hardware and software items used to test the haptic belt are listed below:

- Haptic belt (as described in Chapter 3)
- Earmuffs
- Blindfold
- Arduino mega 2560
- Laptop with Unity application, an open-source Unity library called Unity Experiment Framework (UXF), and custom C# scripts to interface with the haptic belt.

Stimuli

In the haptic belt's case, each stimulus was one of the seven vibrating motors. These motors were arranged around the front half of the waist. The vibration of each motor represented a specific direction, while the intensity of the vibration represented proximity. The stimuli, or haptic cues, have been described in detail in chapter3.[12]

Task

On exposure to each stimulus, the participant had to verbally indicate the perceived direction as their response during part1 of the session, while direction and proximity during part2. In part 1, which was direction-only scenario, participants' response could be any direction from a set of seven clock-face directions ranging from 9 o'clock to 3 o'clock. And in part2, which was direction-and-proximity scenario, participants' response had to be near or far proximity in addition to any direction from a set of seven clock-face directions ranging from 9 o'clock to 3 o'clock. Participants were allowed to verbally ask to repeat (re-expose) the exposed stimulus as often as required until they were ready to indicate their response. Furthermore, participants had to fill out two sets of questionnaires (experienced workload and usability) at the end of both parts of the session. Finally, an informal interview was done at the end of the session.

With the above setup, each of the twelve participants tested the haptic belt. The task design, data collected, and the procedure followed have been

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[12] Chapter 3, section 3.2.1, haptic belt

described in detail in Chapter3.[13] The objective and subjective data collected during the testing of the haptic belt are presented and discussed in the following section.

4.1.2 Results & Discussion

This subsection presents results for the five variables of interest:

- accuracy
- time taken
- repeats taken
- experienced mental workload
- system usability score

The accuracy results are organised into two levels of detail: the stimuli-level and the overall device-level. Stimuli-level results give an insightful summary of the device tested; however, only device-level results are used for statistical comparisons to address relevant research questions. Therefore, device-level overall results are provided for all variables of interest.

Accuracy

Figure 4.1 presents a visual summary of the accuracy and precision for each stimulus during part1 (direction-only) and part2 (direction-and-proximity) of the tests. It shows that the accuracy decreased during part2 of the tests - there are more light red coloured blocks along the white diagonal 100% accuracy line.

[13] Chapter 3, section 3.3, 3.4, 3.5

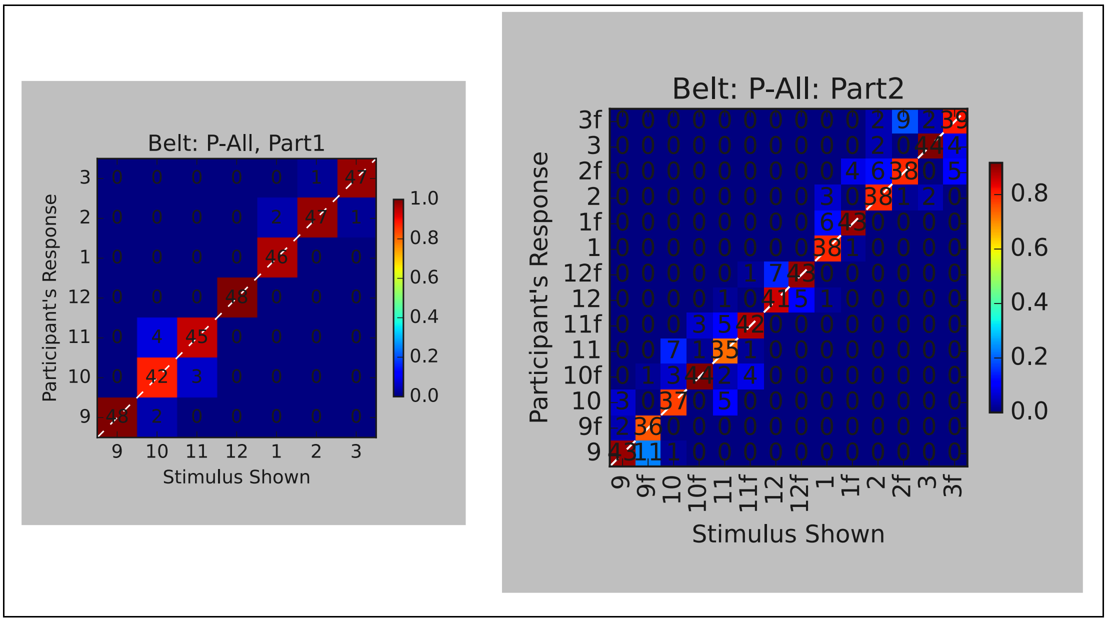

Figure 4.1: Summary of accuracy during direction-only and direction-and-proximity parts of the tests for the haptic belt: (Left) Response matrix for the direction-only part, (Right) Response matrix for direction-and-proximity part

However, the overall accuracy during each part of the tests is used for comparisons. Therefore, Figure 4.2 shows the mean belt accuracy during each part of the tests as the bar heights. The red points represent the mean accuracies of the participants. Error bars represent 95% confidence intervals for the mean of the accuracy for each part.

During part 1, mean accuracy was 96% (94, 98), while during part 2, it was 83% (77, 90). This equates to a Cohen's effect size (dz) value of 1.63. The accuracy comparison between part 2 and part 1 using a (matched pairs) t-test shows a significant difference ($t=-4.72$, $p<0.001$). The significant difference and the large effect size suggest that there is a meaningful decrease in mean accuracy during part 2 of the tests compared to part 1.

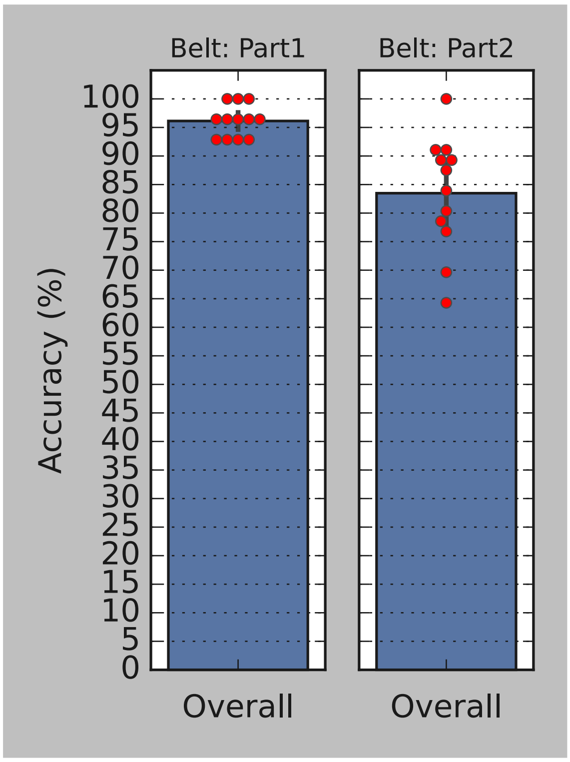

Figure 4.2: Mean accuracy during direction-only and direction-and-proximity parts of the tests for the haptic belt. Error bars represent the 95% confidence interval for the mean.

Time-taken

Figure 4.3 shows the mean time-taken per trial during each part of the tests as the bar heights. The red points represent the mean time-taken by the participants. Error bars represent 95% confidence intervals for the mean of the time-taken (per trial) for each part.

During part 1, mean time-taken was 4 seconds (3.3, 4.8), while during part 2, it was 4.9 seconds (4, 5.8). This equates to a Cohen's effect size (dz) value of 1.93. The time-taken comparison between part 2 and part 1 using a (matched pairs) t-test shows a significant difference ($t=6.5$, $p<0.001$). The significant difference and the large effect size suggest that there is a meaningful increase in the time-taken during part 2 of the tests compared to part 1.

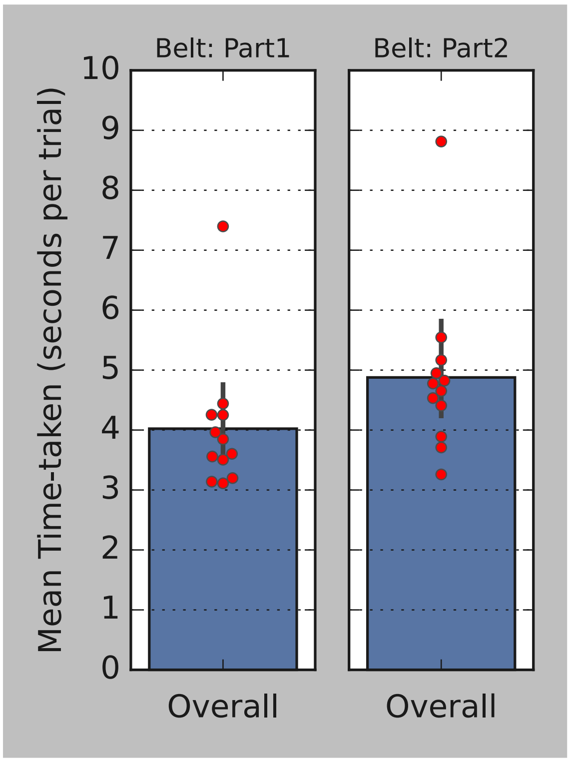

Figure 4.3: Mean time-taken during direction-only and direction-and-proximity parts of the tests for the haptic belt. Error bars represent the 95% confidence interval for the mean.

Repeats-taken

Figure 4.4 shows the mean number of times a given stimulus was repeated/replayed per trial before the participant reported their response during each part of the tests. The mean repeats-taken per trial for each part is shown by the bar heights. The red points represent the mean number of repeats taken by the participants. Error bars represent 95% confidence intervals for the mean of the repeats-taken (per trial) for each part.

During part 1, mean repeats-taken (per trial) was 0.08 (0.01, 0.14), while during part 2, it was 0.09 (0, 0.18). This equates to a Cohen's effect size (dz) value of 0.97. The repeats-taken comparison between part 2 and part 1 using a (matched pairs) t-test shows a lack of significant difference (t=0.53, p=0.6). The lack of significant difference suggests that there is no meaningful increase or decrease in the repeats-taken during part 2 of the tests compared to part 1. It shows that participants requested negligible repeats/replays of the stimuli after first exposure during both parts of the tests.

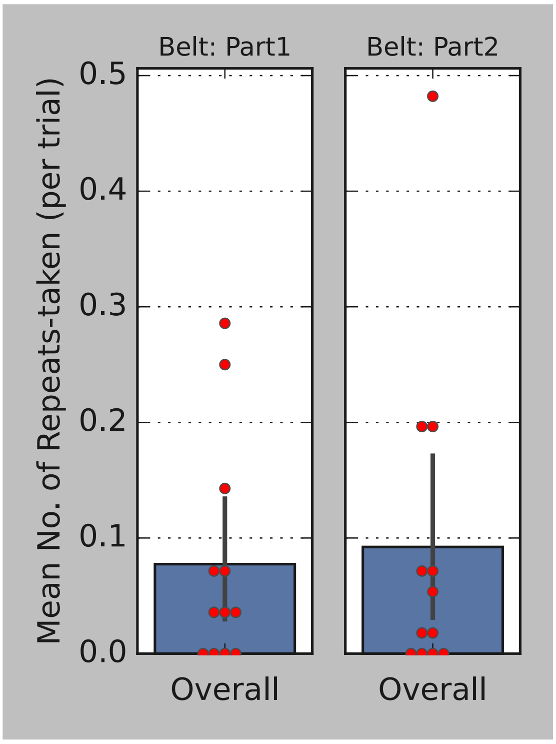

Figure 4.4: Mean repeats-taken during direction-only and direction-and-proximity parts of the tests for the haptic belt. Error bars represent the 95% confidence interval for the mean.

Experienced mental workload

Figure 4.5 shows the mean mental workload experienced by the participants during each part of the tests as the bar heights. The red points represent participants' task load index (TLX) scores. Error bars represent 95% confidence intervals for the mean of the TLX scores for each part.

During part 1, mean mental workload experienced as TLX score was 29 (17, 41), while during part 2, it was 47 (33, 61). This equates to a Cohen's effect size (dz) value of 1.38. The TLX score comparison between part 2 and part 1 using a (matched pairs) t-test shows a significant difference ($t=4.8$, $p<0.001$). The significant difference and the large effect size suggest that there is a meaningful increase in experienced mental workload during part 2 of the tests compared to part 1. It shows that participants experienced a higher mental workload during part 2 (direction-and-proximity) of the tests.

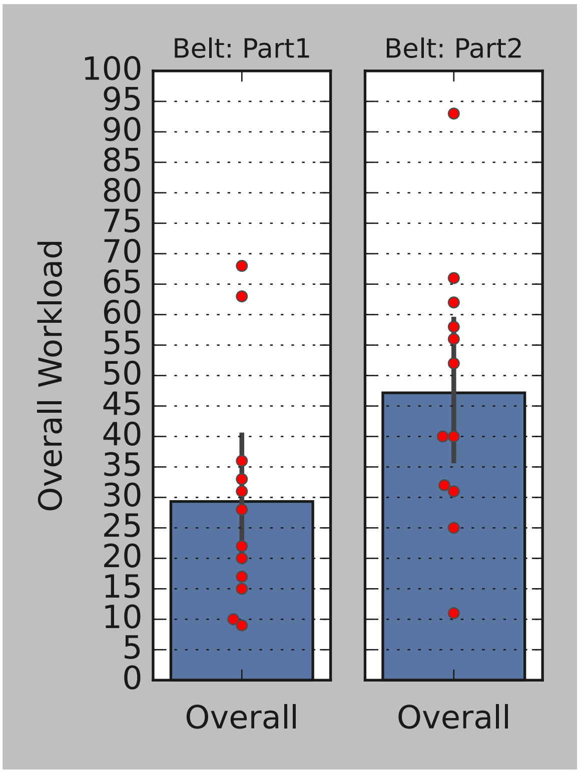

Figure 4.5: Mean task load index score during direction-only and direction-and-proximity parts of the tests for the haptic belt. Error bars represent the 95% confidence interval for the mean.

System usability score

Figure 4.6 shows the mean System Usability Scale (SUS) score during each part of the tests as bar heights. The red points represent participants' perceived system usability score. Error bars represent 95% confidence intervals for the mean of the SUS scores for each part.

During part 1, mean SUS score was 71 (62, 81), while during part 2, it was 66 (57, 76). This equates to a Cohen's effect size (dz) value of 0.37. The SUS score comparison between part 2 and part 1 using a (matched pairs) t-test shows a lack of significant difference (t=-1.3, p=0.22). The lack of significant difference suggests that there is no meaningful increase or decrease in the perceived usability during part 2 of the tests compared to part 1.

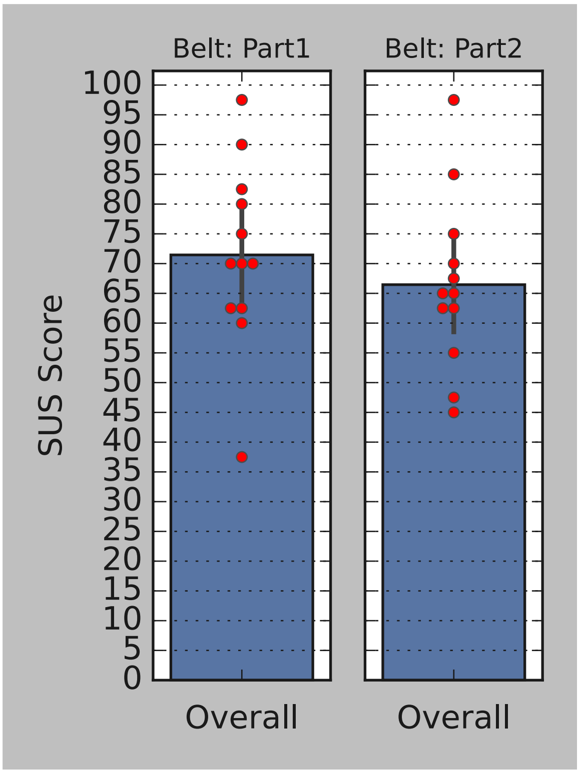

Figure 4.6: Mean System Usability Score (SUS) during direction-only and direction-and-proximity parts of the tests for the haptic belt. Error bars represent the 95% confidence interval for the mean.

Comparison: Direction-only vs Direction-and-proximity

Table 4.2 presents the results for each variable of interest for the belt. It compares the performance during part2 to part1. The null hypothesis tested is that there is no difference between the (within-subjects) means during part1 and part2 of the tests. The statistics given are means with 95% confidence intervals for the given means, t-values for observing such a result for the given dependent variable given the null hypothesis is true, the associated likelihood p-value of observing such an effect, and the Cohen’s effect size (dz) value. The red circle means a statistically significant decline was detected in the performance for the given variable during part2 relative to part1 of the tests. The yellow equality sign means no statistically significant difference was detected in the performance for the given variable during part2 relative to part1. Finally, the green circle means a statistically significant improvement was detected in the performance for the given variable during part2 relative to part1 of the tests.

Table 4.2: Comparison of with-in subjects' performance between the direction-only and direction-and-proximity parts of the tests for the haptic belt

Variable of Interest	Belt during Part2 (compared to Part1)		Belt during Part1
Accuracy	●	83% (t=-4.72, p<0.001, dz=1.63)	96%
Time-taken	●	4.9 seconds per trial (t=6.5, p<0.001, dz=1.93)	4 seconds per trial
Repeats-taken	=	0.09 repeats per trial (t=0.53, p=0.6, dz=0.97)	0.08 repeats per trial
Experienced mental workload	●	47 TLX (t=4.8, p<0.001, dz=1.38)	29 TLX (Score out of 100)
Perceived system-usability	=	66 SUS (t=-1.3, p=0.22, dz=0.37)	71.5 SUS (Score out of 100)

Translating the results, shown in Table 4.2, into practical significance, the haptic belt user will take more instructions (accuracy) and more time per instruction (time-taken) for direction and proximity guidance. This will lead to a larger accumulative time taken to navigate. Furthermore, user will find the device more mentally demanding. Therefore, with the given design of the belt and haptic cues, the haptic belt is more intuitive and effective for direction-only guidance.

In this section, a reference point has been established to compare other devices. The haptic belt forms a good reference point as it has been widely tested and liked for its performance and wearability by the research community. In the next section, the haptic wristband's results are presented - independent of the belt; followed by another section which compares the performance of the belt and wristband.

4.2 The Haptic Wristband

Single-element displays are the most basic form of haptic displays. They consist of only one actuator to deliver the required information to the user. The most common examples of single-element displays are haptic wristbands. They are widely used by the public in the form of smartwatches (Wang et al., 2016; Sunu Band, 2023; Wayband, 2023). In the research realm, there are examples of haptic wristbands being tested as an assistive aid. For example, two single-element wristbands, one on each arm, were used to assist a deafblind participant do horse riding more independently (Ogrinc et al., 2018). The single-element form allows for wearable, portable, and cost-effective design. One disadvantage of vibrotactile devices is the rapid adaptability of the cutaneous receptors.

The single-element haptic feature of the wristbands is mostly used for alerting the user of an incoming message, call, or notification. However, their application as a navigational aid has not been thoroughly explored. This could be rooted in a notion that a single-element display is binary in resolution and therefore limited in its scope for other applications such as a haptic navigational aid (Kaczmarek et al., 1991).

Furthermore, the existing cases of evaluations of the haptic wristbands have been based on objective measures, such as accuracy and time-taken, while the subjective measures have been left unaccounted for during these evaluations, such as the experienced mental workload and the perceived usability.

The subsections below present the experimental setup used to collect data for the objective and subjective measures of the haptic wristband. It also presents the results as graphs for each variable of interest, accompanied by a discussion where needed.

4.2.1 Experimental Setup

This subsection describes the experimental setup used for testing the haptic wristband. The experimental setup can be explained in terms of four aspects: participants, apparatus, stimuli, and task. The explanation should allow replication of the experimental setup.

Participants

Twelve sighted individuals between the ages of 23 and 59 tested the haptic belt. All participants were right-handed, six males and six females, median age of 33, and a mean age of 39 ± nine years of standard deviation.

As previously mentioned in chapter3, the same twelve participants tested each of the five prototypes over five sessions. Sessions for a given participant were separated by a significant amount of time. The testing order of prototypes was counterbalanced across participants to avoid learning effects as much as possible. The exact session numbers for haptic wristband testing are summarised in Table 4.3.

Table 4.3: Participants' session numbers for haptic wristband tests

Participant	Session no.
P1, P2	5th
P3, P4	4th
P5, P6	5th
P7, P8	2nd
P9, P10	1st
P11, P12	1st

Apparatus

Hardware and software items used to test the haptic wristband are listed below:

- Haptic wristband (as described in Chapter 3)
- Earmuffs
- Blindfold
- Arduino mega 2560
- Laptop with Unity application, an open-source Unity library called Unity Experiment Framework (UXF), and custom C# scripts to interface with the haptic belt.

Stimuli

In the haptic wristband's case, each stimulus was one of the seven vibrating patterns produced on a single vibration motor. The motor was placed on the dorsal side of the left wrist, just like a watch. Each vibration pattern of pulses represented a specific direction, while the intensity of the vibration represented proximity. The stimuli, or haptic cues, have been described in detail in chapter3.[14]

Task

On exposure to each stimulus, participants had to verbally indicate the perceived direction as their response during part1 of the session, while direction and proximity during part2. Participants were allowed to verbally ask to repeat (re-expose) the exposed stimulus as often as required until they were ready to indicate their response. Like in the case of the haptic belt, during part 1, which was direction-only scenario, participants' response could be any direction from a set of seven clock-face directions ranging from 9 o'clock to 3 o'clock. And in part2, which was direction-and-proximity scenario, participants' response had to be near or far proximity in addition to any direction from a set of seven clock-face directions ranging from 9 o'clock to 3 o'clock. Furthermore, participants had to fill out two sets of questionnaires (experienced workload and usability) at the end of each part of the session. Finally, an informal interview was done at the end of the session.

With the above setup, each of the twelve participants tested the haptic wristband. The task design, data collected, and the procedure followed have been described in detail in Chapter3.[15] The objective and subjective data collected during the testing of the haptic wristband are presented and discussed in the following section.

4.2.2 Results & Discussion

This subsection presents results for the five variables of interest:

- accuracy
- time taken
- repeats taken
- experienced mental workload
- system usability score

The accuracy results are organised into two levels of detail: the stimuli-level and the overall device-level. Stimuli-level results give an insightful summary of the device tested; However, only device-level results are used for

[14] Chapter3, section3.2.1, haptic wristband
[15] Chapter3, section3.3, 3.4, 3.5

statistical comparisons to address relevant research questions. Therefore, device-level overall results are provided for all variables of interest.

Accuracy

Figure 4.7 presents a visual summary of the accuracy and precision for each stimulus during part1 (direction-only) and part2 (direction-and-proximity) of the tests. It shows that the accuracy increased during part2 of the tests - there are more red-coloured blocks along the white diagonal 100% accuracy line.

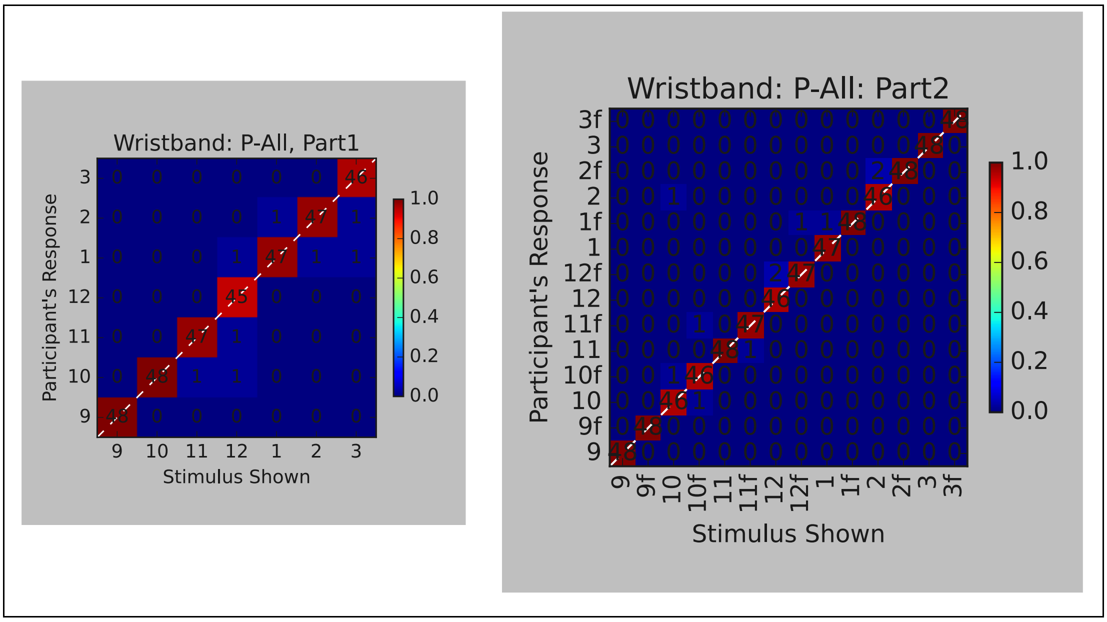

Figure 4.7: Summary of accuracy during direction-only and direction-and-proximity parts of the tests for the haptic wristband: (Left) Response matrix part1, (Right)

However, the overall accuracy during each part of the tests that is used for comparisons. Therefore, Figure 4.8 shows the mean wristband accuracy during each part of the tests as the bar heights. The red points represent the mean accuracies of the participants. Error bars represent 95% confidence intervals for the mean of the accuracy for each part.

During part 1, mean accuracy was 97.6% (95.4, 99.9), while during part 2, it was 98.4% (97, 99.8). This equates to a Cohen's effect size (dz) value of 0.18. The accuracy comparison between part 2 and part 1 using a (matched pairs) t-test shows a lack of significant difference (t=0.58, p=0.58). The lack of significant difference suggests that there is no meaningful increase or decrease in the accuracy during part 2 of the tests compared to part 1.

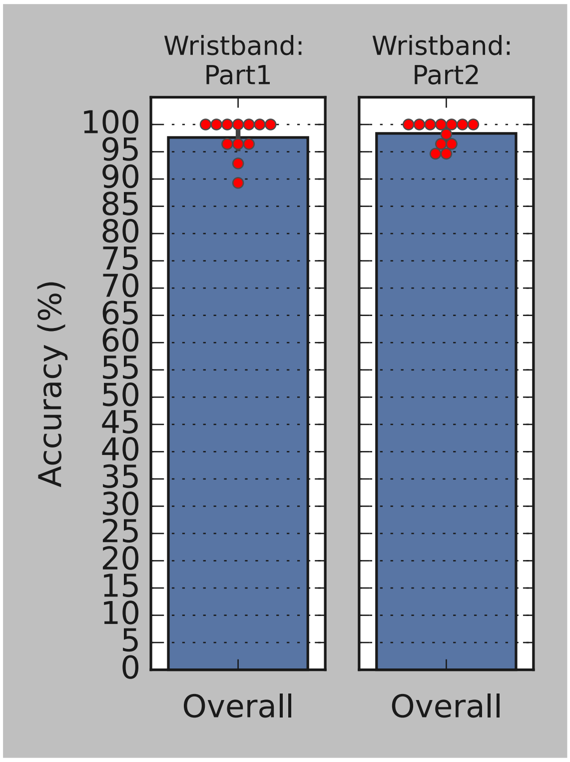

Figure 4.8: Mean accuracy during direction-only and direction-and-proximity parts of the tests for the haptic wristband. Error bars represent the 95% confidence interval for the mean.

Time-taken

Figure 4.9 shows the mean time-taken per trial during each part of the tests the bar heights. The red points represent the mean time-taken by the participants. Error bars represent 95% confidence intervals for the mean of the time-taken (per trial) for each part.

During part 1, mean time-taken was 6.1 seconds (5.3, 6.9), while during part 2, it was 5.7 seconds (5.3, 6.0). This equates to a Cohen's effect size (dz) value of 0.41. The time-taken comparison between part 2 and part 1 using a (matched pairs) t-test shows a lack of significant difference (t=-1.43, p=0.18). The lack of significant difference suggests that there is no meaningful increase or decrease in the time-taken per trial during part 2 of the tests compared to part 1.

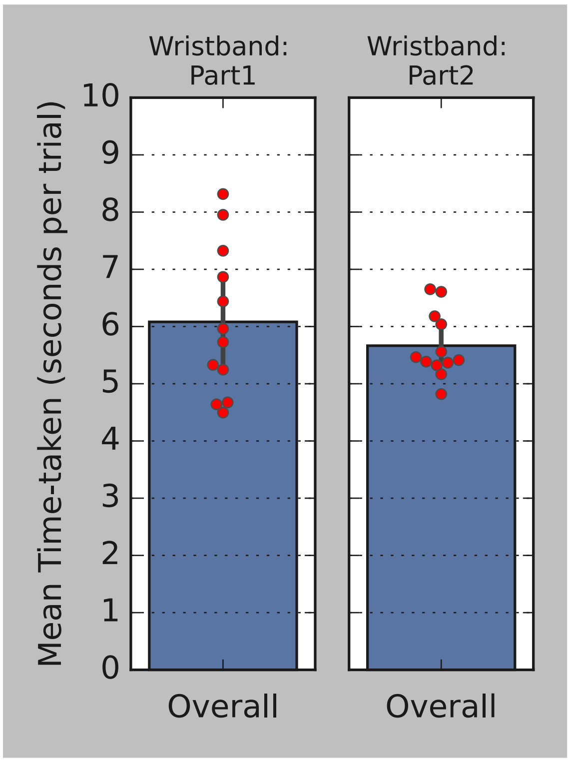

Figure 4.9: Mean time-taken during direction-only and direction-and-proximity parts of the tests for the haptic wristband. Error bars represent the 95% confidence interval for the mean.

Repeats-taken

Figure 4.10 shows the mean number of times a given stimulus was repeated/replayed per trial before the participant reported their response during each part of the tests. The mean repeats-taken per trial for each part is shown by the bar heights. The red points represent the mean number of repeats taken by the participants. Error bars represent 95% confidence intervals for the mean of the repeats-taken (per trial) for each part.

During part 1, mean repeats-taken (per trial) was 0.01 (0.0, 0.03), while during part 2, it was 0.02 (0.0, 0.04). This equates to a Cohen's effect size (dz) value of 0.12. The repeats-taken comparison between part 2 and part 1 using a (matched pairs) t-test shows a lack of significant difference (t=0.45, p=0.66). The lack of significant difference suggests that there is no meaningful increase or decrease in the repeats-taken during part 2 of the tests compared to part 1. It shows that participants requested negligible repeats/replays of the stimuli after first exposure during both parts of the tests.

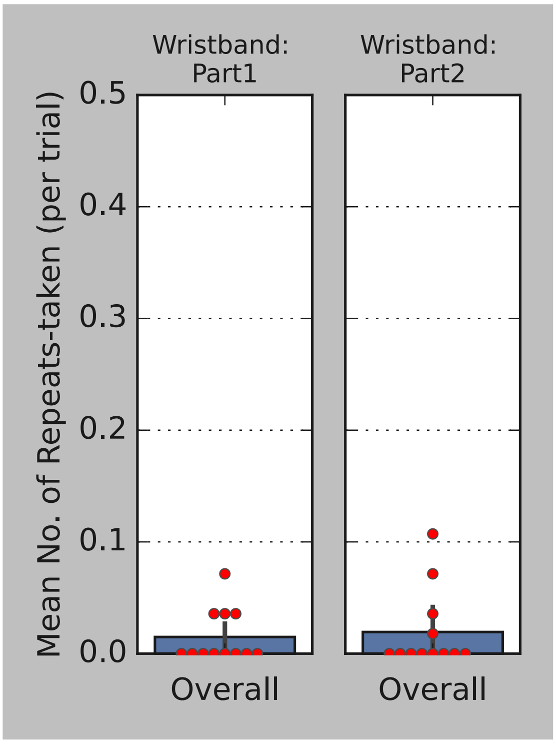

Figure 4.10: Mean repeats-taken during direction-only and direction-and-proximity parts of the tests for the haptic wristband. Error bars represent the 95% confidence interval for the mean.

Experienced mental workload

Figure 4.11 shows the mean mental workload experienced by the participants during each part of the tests as the bar heights. The red points represent participants' task load index (TLX) scores. Error bars represent 95% confidence intervals for the mean of the TLX scores for each part.

During part 1, mean mental workload experienced as TLX score was 36 (22, 51), while during part 2, it was 39 (22, 55). This equates to a Cohen's effect size (dz) value of 0.16. The TLX score comparison between part 2 and part 1 using a (matched pairs) t-test shows a lack of significant difference (t=0.56, p=0.58). The lack of significant difference suggests that there is no meaningful increase or decrease in the experienced mental workload during part 2 of the tests compared to part 1.

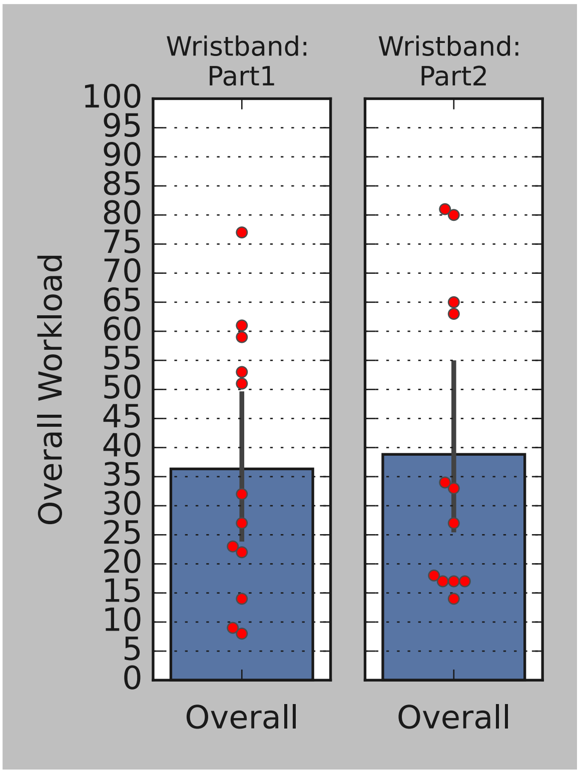

Figure 4.11: Mean task load index score during direction-only and direction-and-proximity parts of the tests for the haptic wristband. Error bars represent the 95% confidence interval for the mean.

System usability score

Figure 4.12 shows the mean System Usability Scale (SUS) score during each part of the tests as bar heights. The red points represent participants' perceived system usability score. Error bars represent 95% confidence intervals for the mean of the SUS scores for each part.

During part 1, mean SUS score was 74 (65, 83), while during part 2, it was 72 (64, 80). This equates to a Cohen's effect size (dz) value of 0.25. The SUS score comparison between part 2 and part 1 using a (matched pairs) t-test shows a lack of significant difference (t=-0.88, p=0.39). The lack of significant difference suggests that there is no meaningful increase or decrease in the perceived usability during part 2 of the tests compared to part 1.

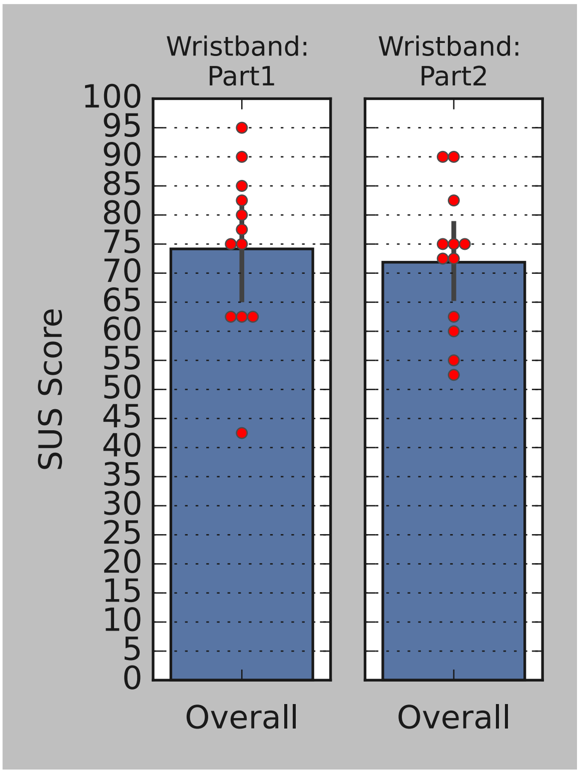

Figure 4.12: Mean System Usability Score (SUS) during direction-only and direction-and-proximity parts of the tests for the haptic wristband. Error bars represent the 95% confidence interval for the mean.

Comparison: Direction-only vs Direction-and-proximity

Table 4.4 presents the results for each variable of interest for the wristband. It compares the performance during part2 to part1. The null hypothesis tested is that there is no difference between the (within-subjects) means during part1 and part2 of the tests. The statistics given are means with 95% confidence intervals for the given means, t-values for observing such a result for the given dependent variable given the null hypothesis is true, the associated likelihood p-value of observing such an effect, and the Cohen's effect size (dz) value. The red circle means a statistically significant decline was detected in the performance for the given variable during part2 relative to part1 of the tests. The yellow equality sign means no statistically significant difference was detected in the performance for the given variable during part2 relative to part1. Finally, the green circle means a statistically significant improvement was detected in the performance for the given variable during part2 relative to part1 of the tests.

Table 4.4: Comparison of with-in subjects' performance between the direction-only and direction-and-proximity parts of the tests for the haptic wristband

Variable of Interest	Wristband during Part2 (compared to Part1)		Wristband during Part1
Accuracy	=	98.4% (t=0.58, p=0.58, dz= 0.18)	97.6%
Time-taken	=	5.7 seconds per trial (t=-1.43, p=0.18, dz= 0.41)	6.1 seconds per trial
Repeats-taken	=	0.02 repeats per trial (t=0.45, p=0.66, dz=0.12)	0.01 repeats per trial
Experienced mental workload	=	39 TLX (t=0.56, p=0.58, dz=0.16)	36 TLX (Score out of 100)
Perceived system-usability	=	72 SUS (t=-0.88, p=0.39, dz=0.25)	74 SUS (Score out of 100)

Translating the results, shown in Table 4.4, into practical significance, the haptic wristband's user, with the given design of the device and haptic cues, will find it as intuitive and effective for direction-only guidance as for direction-and-proximity guidance.

In this section, another reference point has been established to compare other devices. The single-element haptic wristband forms a good secondary reference point as It is the most simple and fundamental form of a vibrotactile device. The following section concludes the chapter by comparing the performance of the multi-element belt to the single-element wristband.

4.3 Comparison: Wristband vs Belt

Previous sections independently present the results of two passive prototypes (the belt and the wristband). This section compares the results of the two prototypes to address the sub-research question. The sub-research question is "How intuitive and effective is a passive vibrotactile device for navigation". A more detailed version is "How intuitive and effective is a single-element vibrotactile wristband compared to a multi-element vibrotactile belt for navigation". Figure 4.13 shows the sub-research question divided into elements.

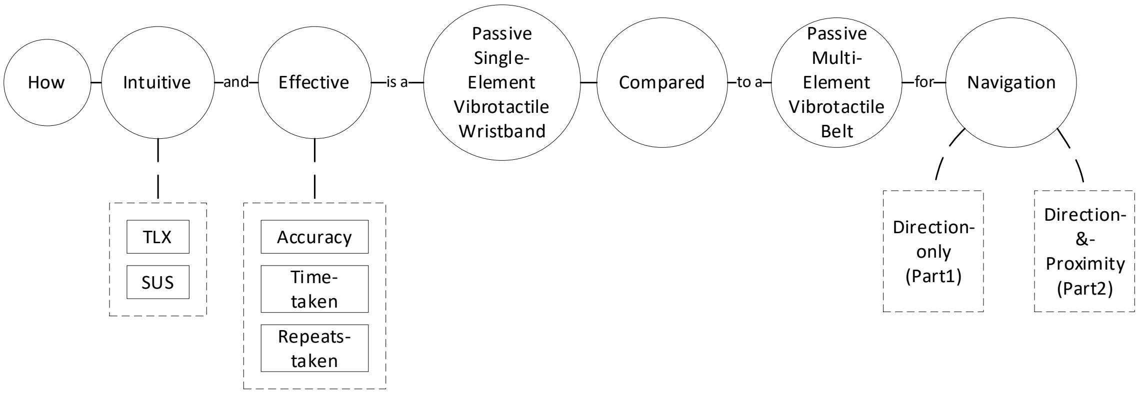

Figure 4.13: Sub-research question for passive vibrotactile devices

Table 4.5 and Table 4.6 show the comparison results for the given devices during the given scenario: direction-only (part1) and direction-and-proximity (part2). The null hypothesis tested is that there is no difference between the (between-subjects) means of the given devices during the given part of the tests. The statistics given are means with 95% confidence intervals for the given means, t-values for observing such a result for the given dependent variable given the null hypothesis is true, the associated likelihood p-value of observing such an effect, and the Cohen's effect size (d) value. The red circle means a statistically significant decline was detected in the performance for the given devices and the variable during the given part of the tests. The yellow equality sign means no statistically significant difference was detected in the performance for the given devices and the variable during the given part of the tests. Finally, the green circle means a statistically significant improvement was detected in the performance for the given devices and the variable during the given part of the tests.

Table 4.5: Comparison of the wristband to the belt for direction-only scenario

Variable of Interest	Wristband (compared to belt)		Belt
Accuracy	=	97.6% (t=1.14, p=0.27, d=0.47)	96%

Time-taken	●	6.1 seconds per trial (t=4.09, p=0.004, d=1.67)	4 seconds per trial
Repeats-taken	●	0.01 repeats trial (t=-2.14, p=0.04, d=0.97)	0.08 repeats per trial
Experienced mental workload	=	36 TLX (t=0.81, p=0.42, d=0.33)	29 TLX (Score out of 100)
Perceived system-usability	=	74 SUS (t=0.44, p=0.66, d=0.18)	71.5 SUS (Score out of 100)

Translating the results, shown in Table 4.5, into practical significance, the haptic belt user will take less time per instruction (time-taken) for guidance. This will lead to a smaller accumulative time taken to navigate for the belt. Therefore, with the given design of the belt and haptic cues, the haptic belt is more effective in terms of time-taken for direction-only guidance. However, the performance of a single-element haptic wristband is similar for the other four variables of interest.

Table 4.6: Comparison of the wristband to the belt for direction-and-proximity scenario

Variable of Interest	Wristband (compared to belt)		Belt
Accuracy	●	98.4% (t=5.01, p<0.001, d= 2.06)	83%
Time-taken	=	5.7 seconds per trial (t=1.81, p=0.08, d= 0.73)	4.9 seconds per trial
Repeats-taken	=	0.02 repeats per trial (t=-1.73, p=0.1, d=0.68)	0.09 repeats per trial

Experienced mental workload	=	39 TLX (t=-0.85, p=0.4, d=0.35)	47 TLX (Score out of 100)
Perceived system-usability	=	72 SUS (t=0.98, p=0.34, d=0.4)	66.5 SUS (Score out of 100)

Translating the results, shown in Table 4.6, into practical significance, the haptic wristband user will take fewer instructions (accuracy) for guidance. Therefore, with the given design of the wristband and haptic cues, the haptic wristband is more effective in terms of accuracy for direction-and-proximity guidance. For other variables of interest, the haptic wristband's performance is the same as the haptic belt for direction-and-proximity guidance.

4.4 Findings based on the Interviews

As mentioned in Chapter 3, each session ended with an informal interview to collect participants' experience-based qualitative data. As a recap, questions were mostly open-ended, a few examples are as follows:

- What do they think about this prototype?
- What did they like about the prototype?
- What did they dislike about the prototype?
- How would they rank the prototypes so far tested?

This section presents the key findings from the analysis of the notes that were made during the interviews.

4.4.1 Haptic Belt

The recurring patterns of comments and issues per the participants, along with the number of participants who notified each pattern are listed below:

- Difficulty with specific directions: Several participants (at least 6 participants) mentioned struggling with directions 10, 11, 1, and 2.
- Preference for passive prototypes: Many participants (at least 6 participants) expressed a preference for passive prototypes.

- Challenges with intensity: Multiple participants (at least 4 participants) mentioned difficulties with intensity, either finding it too tickly or not different enough.
- Variations in performance: Participants (at least 2 participants) noted variations in their performance, such as finding one side of the body easier than the other or experiencing fatigue or adaptation towards the end of the testing.
- Positive feedback on comfort and ease of use: Several participants (at least 4 participants) mentioned finding the device comfortable to wear and easy to use once they got the hang of it.

Participants also made suggestions for improving the prototype and haptic cues' design. General themes of suggestions are given below:

- The suggestion of using different pulse patterns for indicating different proximities: Some participants (at least 3 participants) mention the idea of using two pulses for far distances and one pulse for near distances as a potentially better approach than relying solely on intensity.
- The consideration of pulsation as a clearer indicator for proximity: Some suggested (at least 2 participants) that pulsation would be a clearer indicator of proximity compared to intensity.
- The idea of reducing the resolution of direction: Some suggested (at least 2 participants) propose reducing the resolution of direction to the diagonal left and diagonal right, making it easier to interpret and differentiate between directions.
- The concept of unique casings for vibration motors: one participant suggested using unique casings for the vibration motors to provide a distinct feeling for each direction, enhancing the user experience.
- One-off suggestions: There were some one-off suggestions made by the participants. For example, moving 9 further back and swiping vibration from 10 to 9 and from 12 to 11 (and vice versa) to make 10 and 11 clear directions clearer, and the vibration difference could be bigger.

4.4.2 Haptic Wristband

The recurring patterns of comments and issues per the participants, along with the number of participants who experienced each pattern are listed below:

- Device preference: Several participants (at least 3) found the wristband device to be less complex and easier to use than the dial or other devices.
- Mode preference: Many participants (at least 4) preferred the passive mode over the active mode.
- Mental demand: Some participants (at least 2) found it mentally demanding to keep track of the number of vibrations and intensity.
- Difficulty in distinguishing: A few participants (at least 2) had difficulty distinguishing between near and far vibrations.
- Conflicting numbers: Several participants (at least 2) found the counting numbers to be conflicting with the clock numbers.
- Difficulty in remembering: Some participants (at least 2) found it difficult to remember two numbers for the direction.
- Annoying waiting time: A few participants (at least 2) found the waiting time to be annoying for the vibration count to finish, for example, seven vibrations for the 3 o'clock direction.

Participants also made suggestions for improving the prototype and haptic cues' design. General themes of suggestions are given below:

- Dual wristband recommendation: Some participants (at least 3) suggested using two wristbands, one for each arm, for improved navigation.
- Vibration length for distance indication: Some participants (at least 3) suggested using vibration length to indicate distance instead of intensity.
- Different counting method for speed: Some participants (at least 2) suggested using a different counting method for left and right directions to speed up navigation.
- One-off suggestions: There were some one-off suggestions made by the participants. For example, making a clear distinction between different intensities would be better for navigation, adding a button to recalibrate intensities for near and far distances, and using a silicon casing to keep the vibrator in place.

4.5 Conclusion

The multi-element haptic belt was more effective (time-taken), as a navigation display for direction-only guidance, than the single-element haptic wristband.

The single-element haptic wristband was more effective (accuracy), as a navigation display for direction-and-proximity guidance, than the multi-element haptic belt.

The single-element haptic wristband was as intuitive, as a navigation display for direction-only and direction-and-proximity guidance, as the multi-element haptic belt.

This comparison also shows that the lack of thorough investigation based on the notion that the single-element display is binary in resolution and, therefore, inferior to multi-element displays is unwarranted.

The findings from the interview data point towards interesting observations to keep in mind, improvements to make, and issues to solve during future research projects.

Chapter 5
Active Proprioceptive Devices: Performance of Seeking Direction and Proximity

This chapter evaluates the performance (intuitiveness and effectiveness) of the three active proprioceptive vibrotactile devices as navigational devices: two joysticks (round and octagonal) and a haptic dial. The reason for choosing active proprioceptive devices is to address the lack of investigation of their performance as displays in a navigational context.[16] For example, joysticks are commonly used to give directions to machines because they map well with the user's sense of proprioception. In contrast, this chapter investigates the performance of the reverse usage of the joystick as a navigation display, i.e. seeking direction and proximity. The reason for choosing three different active proprioceptive devices is to explore the effects of subtle hardware and haptic cue differences on the performance of seeking direction and proximity.

This chapter has five main sections, one for each active proprioceptive vibrotactile device, one for comparing the three devices across two parts (direction-only part1 and direction-and-proximity part2), and the last for presenting the qualitative findings which are based on the informal interviews. First four sections cover details of the experimental setup, present and discuss results, and compare the performance of the given device across two parts locally. Whereas the last section lists interesting comments, issues, and improvement suggestions made by the participants for each of the devices.

5.1 The Haptic Joystick (Round rim)

Active proprioceptive devices, which are part of the mechano-tactile category, include joysticks. These devices deliver information using the body part's sense of position and orientation. Analogue joysticks are typical devices for giving directions, for example, in gaming and virtual reality, to control machines and remote-control devices. Joysticks are intuitive and effective in actively giving directions because they map well with the user's sense of proprioception. They also require minimal training and can be made wearable and portable. However, can the reverse be true too, that is, can an active proprioceptive

[16] See Chapter 2, section 2.6, identified gaps in knowledge: lack of investigation of active proprioceptive vibrotactile devices for navigation.

device, like a joystick, intuitively and effectively display directions?[17] This section addresses this question using a joystick with a round rim.

The existing evaluations of the haptic devices have been based on objective measures, such as accuracy and time taken. In contrast, subjective measures, such as the experienced mental workload and perceived usability, are left unaccounted for during these evaluations. This narrow objective method of evaluation prevents a deeper understanding of the user experience of the haptic device for a task (Jahedi and Méndez, 2014). This understanding, by having both types of measurements, will allow better user-centred design iterations aimed at improving haptic displays for navigation. A thorough evaluation of navigational haptic devices is a gap in the literature, as explained in Chapter 2.

The subsections below present the experimental setup used to collect data for the objective and subjective measures of the haptic joystick. It also presents the results as graphs for each variable of interest, accompanied by a discussion where needed.

5.1.1 Experimental Setup

This subsection describes the experimental setup used for testing the haptic joystick. The experimental setup is explained in terms of four aspects: participants, apparatus, stimuli, and task. The explanation should allow replication of the experimental setup.

Participants

Twelve sighted individuals, aged between 23 and 59, tested the haptic joystick (round-rimmed). All participants were right-handed, six males and six females, with a median age of 33 and a mean age of 39 ± nine years of standard deviation.

As mentioned in chapter3, the same twelve participants tested each of the five prototypes over five sessions. Sessions for a given participant were separated by a significant amount of time. The testing order of prototypes was counterbalanced across participants to avoid learning effects as much as

[17] See Chapter 2, section 2.6, sub-research-question-2: how intuitive and effective is an active proprioceptive vibrotactile device for navigation?

possible. The exact session numbers for the (round-rimmed) haptic joystick testing are summarised in Table 5.1.

Table 5.1: Participants' session numbers for round-rimmed haptic joystick tests

Participant	Session no.
P1, P2	1st
P3, P4	1st
P5, P6	3rd
P7, P8	4th
P9, P10	3rd
P11, P12	4th

Apparatus

Hardware and software items used to test the round-rimmed haptic joystick are listed below:

- Haptic joystick (round-rimmed) (as described in Chapter 3)
- Earmuffs
- Blindfold
- Arduino mega 2560
- Laptop with Unity application, an open-source Unity library called Unity Experiment Framework (UXF), SCP Toolkit for Windows drivers and XInput wrapper for the Sony controller, and custom C# scripts to interface with the haptic joystick.

Stimuli

In the round-rimmed haptic joystick's case, each stimulus was one of the seven positions along the circumference of the round rim representing a specific direction accompanied by a vibration pattern representing near or far proximities. The stimuli, or haptic cues, have been described in detail in chapter3.[18]

[18] Chapter 3, section 3.2.2, haptic joysticks

Task

On exposure to each stimulus, the participant had to verbally indicate the perceived direction as their response during part1 of the session, while direction and proximity during part2. In part 1, which was the direction-only scenario, participants' response could be any direction from a set of seven clock-face directions ranging from 9 o'clock to 3 o'clock. And in part2, which was the direction-and-proximity scenario, participants' response had to be near or far proximity in addition to any direction from a set of seven clock-face directions ranging from 9 o'clock to 3 o'clock. Participants were allowed to repeat (re-expose) the exposed stimulus as often as required until they were ready to indicate their response. Furthermore, participants had to fill out two sets of questionnaires (experienced workload and usability) at the end of both parts of the session. Finally, an informal interview was done at the end of the session.

With the above setup, each of the twelve participants tested the haptic joystick (round rim). The task design, data collected, and the procedure followed have been described in detail in Chapter3.[19] The objective and subjective data collected during the testing of the haptic joystick are presented and discussed in the following section.

5.1.2 Results & Discussion

This subsection presents results for the five variables of interest:

- accuracy
- time taken
- repeats taken
- experienced mental workload
- system usability score

The accuracy results are organised into two levels of detail: the stimuli-level and the overall device-level. Stimuli-level results give an insightful summary of the device tested; However, only device-level results are used for statistical comparisons to address relevant research questions. Therefore, device-level overall results are provided for all variables of interest.

[19] Chapter 3, section 3.3, 3.4, 3.5

Accuracy

Figure 5.1 presents a visual summary of the accuracy and precision for each stimulus during part1 (direction-only) and part2 (direction-and-proximity) of the tests. It shows that the accuracy increased during part2 of the tests - there are more red-coloured blocks along the white diagonal 100% accuracy line.

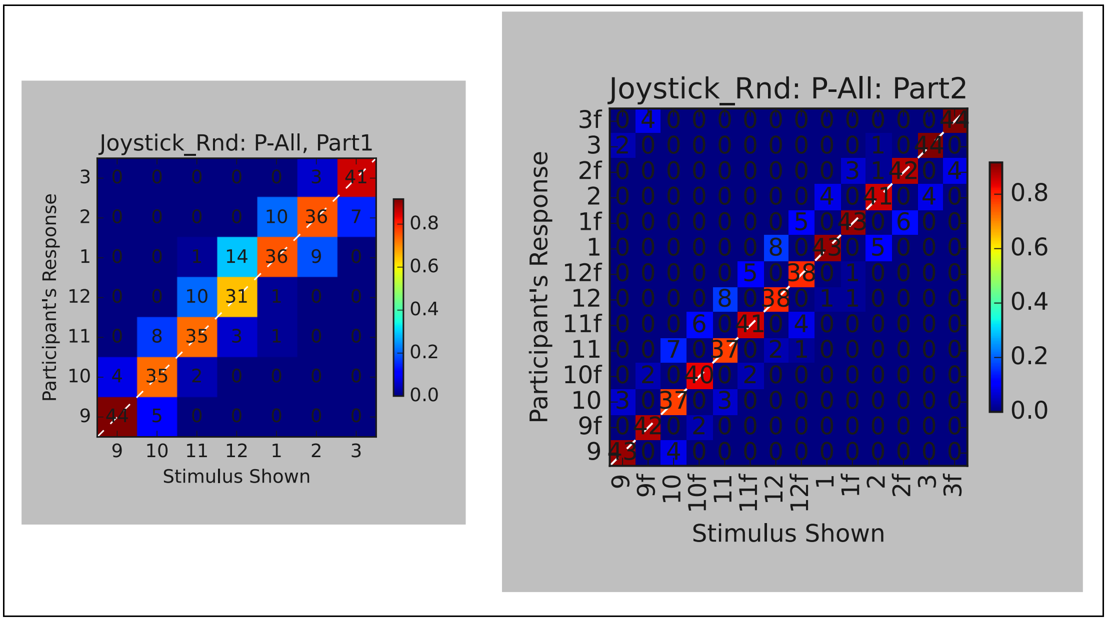

Figure 5.1: Summary of accuracy during direction-only and direction-and-proximity parts of the tests for the round-rimmed joystick: (Left) Response matrix for the direction-only part, (Right) Response matrix for direction-and-proximity part

However, the overall accuracy during each part of the tests is used for comparisons. Therefore, Figure 5.2 shows the mean belt accuracy during each part of the tests as the bar heights. The red points represent the mean accuracies of the participants. Error bars represent 95% confidence intervals for the mean of the accuracy for each part.

During part 1, mean accuracy was 77% (67, 86), while during part 2, it was 85% (79, 92). This equates to a Cohen's effect size (dz) value of 0.66. The accuracy comparison between part 2 and part 1 using a (matched pairs) t-test shows a significant difference (t=2.3, p= 0.04). The significant difference suggests that there is a meaningful increase in mean accuracy during part 2 of the tests compared to part 1.

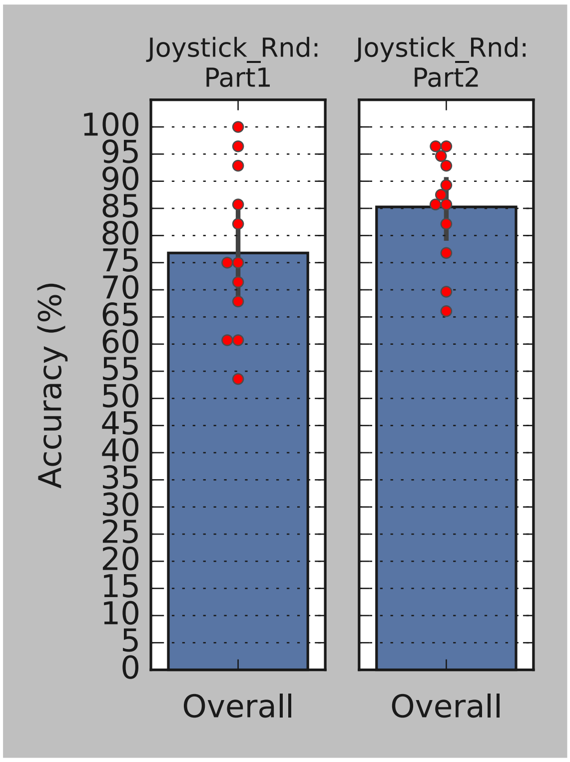

Figure 5.2: Mean accuracy during direction-only and direction-and-proximity parts of the tests for the round-rimmed joystick. Error bars represent the 95% confidence interval for the mean. Error bars represent the 95% confidence interval for the mean.

Time-taken

Figure 5.3 shows the mean time-taken per trial during each part of the tests as the bar heights. The red points represent the mean time-taken by the participants. Error bars represent 95% confidence intervals for the mean of the time-taken (per trial) for each part.

During part 1, mean time-taken was 9.2 seconds (5.7, 12.6), while during part 2, it was 10.4 seconds (7.6, 13.2). This equates to a Cohen's effect size (dz) value of 0.41. The time-taken comparison between part 2 and part 1 using a (matched pairs) t-test shows a lack of significant difference (t= 1.4, p=0.18). The lack of significant difference suggests that there is no meaningful increase or decrease in the time-taken during part 2 of the tests compared to part 1.

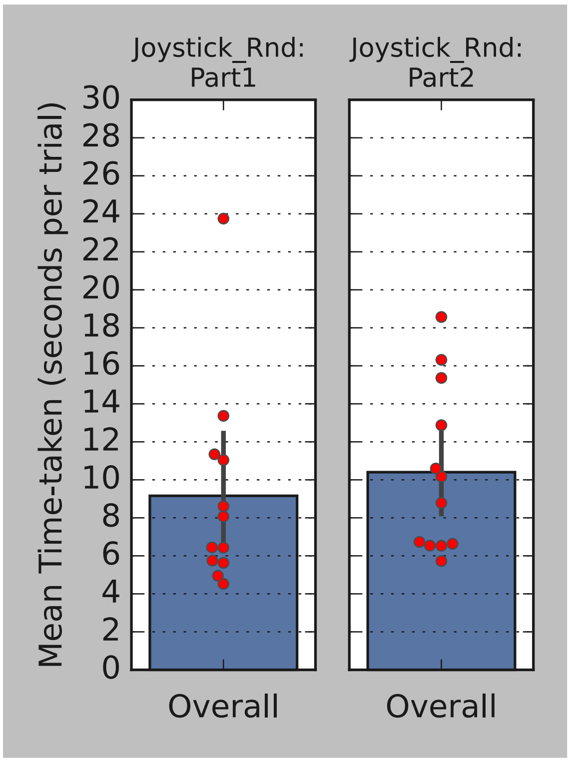

Figure 5.3: Mean time-taken during direction-only and direction-and-proximity parts of the tests for the round-rimmed joystick. Error bars represent the 95% confidence interval for the mean.

Repeats-taken

Figure 5.4 shows the mean number of times a given stimulus was repeated/replayed per trial before the participant reported their response during each part of the tests. The mean repeats-taken per trial for each part is shown by the bar heights. The red points represent the mean number of repeats taken by the participants. Error bars represent 95% confidence intervals for the mean of the repeats-taken (per trial) for each part.

During part 1, mean repeats-taken (per trial) was 2.8 (1.8, 3.7), while during part 2, it was 2.5 (1.5, 3.4). This equates to a Cohen's effect size (dz) value of 0.27. The repeats-taken comparison between part 2 and part 1 using a (matched pairs) t-test shows a lack of significant difference (t=-0.9, p=0.36). The lack of significant difference suggests that there is no meaningful increase or decrease in the repeats-taken during part 2 of the tests compared to part 1. It shows that participants requested negligible repeats/replays of the stimuli after first exposure during both parts of the tests.

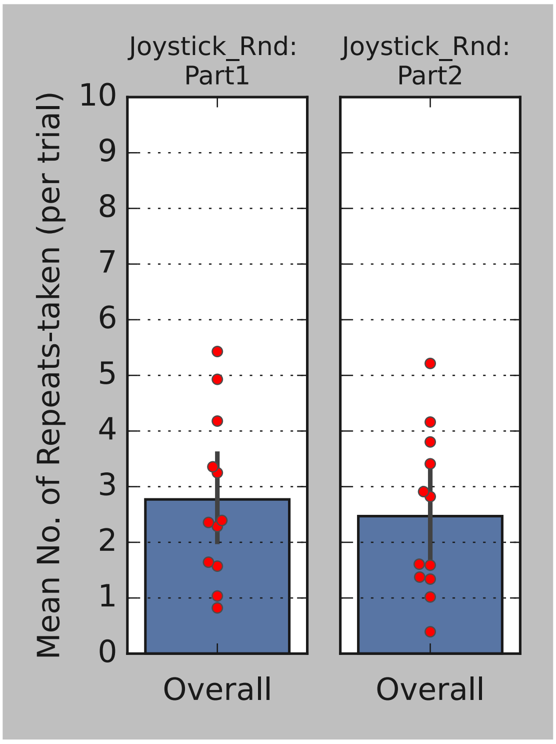

Figure 5.4: Mean number of repeats-taken during direction-only and direction-and-proximity parts of the tests for the round-rimmed joystick. Error bars represent the 95% confidence interval for the mean.

Experienced mental workload

Figure 5.5 shows the mean mental workload experienced by the participants during each part of the tests as the bar heights. The red points represent participants' task load index (TLX) scores. Error bars represent 95% confidence intervals for the mean of the TLX scores for each part.

During part 1, mean mental workload experienced as TLX score was 50 (38, 61), while during part 2, it was 60 (45, 74). This equates to a Cohen's effect size (dz) value of 0.69. The TLX score comparison between part 2 and part 1 using a (matched pairs) t-test shows a significant difference (t=2.3, p=0.04). The significant difference and the large effect size suggest that there is a meaningful increase in experienced mental workload during part 2 of the tests compared to part 1. It shows that participants experienced a higher mental workload during part 2 (direction-and-proximity) of the tests.

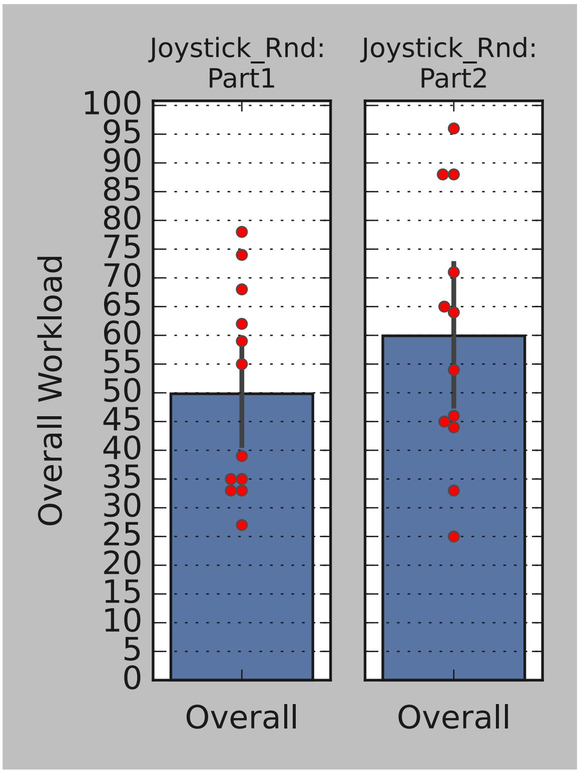

Figure 5.5: Mean task load index score during direction-only and direction-and-proximity parts of the tests for the round-rimmed joystick. Error bars represent the 95% confidence interval for the mean.

System usability score

Figure 5.6 shows the mean System Usability Scale (SUS) score during each part of the tests as bar heights. The red points represent participants' perceived system usability score. Error bars represent 95% confidence intervals for the mean of the SUS scores for each part.

During part 1, mean SUS score was 66 (54, 79), while during part 2, it was 58 (44, 72). This equates to a Cohen's effect size (dz) value of 0.49. The SUS score comparison between part 2 and part 1 using a (matched pairs) t-test shows a lack of significant difference (t=-1.7, p=0.12). The lack of significant difference suggests that there is no meaningful increase or decrease in the perceived usability during part 2 of the tests compared to part 1.

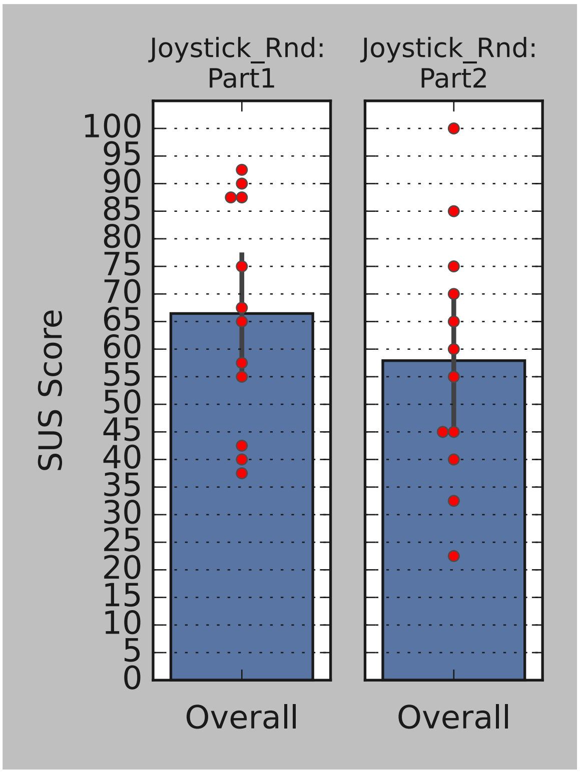

Figure 5.6: Mean System Usability Score (SUS) during direction-only and direction-and-proximity parts of the tests for the round-rimmed joystick. Error bars represent the 95% confidence interval for the mean.

Comparison: Direction-only vs Direction-and-proximity

Table 5.2 presents the results for each variable of interest for the round-rimmed joystick. It compares the performance during part2 to part1. The null hypothesis tested is that there is no difference between the (within-subjects) means during part1 and part2 of the tests. The statistics given are means with 95% confidence intervals for the given means, t-values for observing such a result for the given dependent variable given the null hypothesis is true, the associated likelihood p-value of observing such an effect, and the Cohen's effect size (dz) value. The red circle means a statistically significant decline was detected in the performance for the given variable during part2 relative to part1 of the tests. The yellow equality sign means no statistically significant difference was detected in the performance for the given variable during part2 relative to part1. Finally, the green circle means a statistically significant improvement was detected in the performance for the given variable during part2 relative to part1 of the tests.

Table 5.2: Comparison of with-in subjects' performance between the direction-only and direction-and-proximity parts of the tests for the round-rimmed joystick

Variable of Interest	Joystick_Rnd during Part2 (compared to Part1)		Joystick_Rnd during Part1
Accuracy		85% (t=2.3, p= 0.04, dz= 0.66)	77%
Time-taken	=	10.4 seconds per trial (t= 1.4, p=0.18, dz=0.41)	9.2 seconds per trial
Repeats-taken	=	2.5 repeats per trial (t=-0.9, p=0.36, dz=0.27)	2.8 repeats per trial
Experienced mental workload		60 TLX (t=2.3, p=0.04, dz=0.69)	50 TLX (Score out of 100)
Perceived system-usability	=	58 SUS (t=-1.7, p=0.12, dz=0.49)	66.5 SUS (Score out of 100)

Translating the results, shown in Table 5.2, into practical significance, the (round-rimmed) haptic joystick's user will take fewer instructions (accuracy) and the same amount of time per instruction (time-taken) for direction and proximity guidance, which will lead to a smaller accumulative time taken to navigate. However, the user will find the device more mentally demanding. Therefore, with the given design of the round-rimmed joystick and haptic cues, the device is more intuitive for direction-only guidance while more effective for direction-and-proximity guidance.

This section has established a reference point to compare other active proprioceptive devices. The round-rimmed joystick forms a good reference point as it is the most minimalist of the three active devices tested. In the next section, the octagonal-rimmed haptic joystick's results are presented –

independent of other devices; followed by a haptic dial design; and finally, the last section compares the performance of these active proprioceptive devices tested.

5.2 The Haptic Joystick (Octagonal rim)

The joystick with an octagonal rim is a variation of the round-rimmed joystick. The octagonal-rim joystick was tested to investigate the effect of such a subtle change to the haptic stimuli on the performance. The idea behind the octagonal rim is to introduce external haptic cues to aid proprioception. This section addresses the same question as the round-rim joystick but uses an octagonal rim instead.

The subsections below present the experimental setup used to collect data for the objective and subjective measures of the haptic joystick. It also presents the results as graphs for each variable of interest, accompanied by a discussion where needed.

5.2.1 Experimental Setup

This subsection describes the experimental setup used for testing the haptic joystick. The experimental setup is explained in terms of four aspects: participants, apparatus, stimuli, and task. The explanation should allow replication of the experimental setup.

Participants

Twelve sighted individuals, aged between 23 and 59, tested the haptic joystick (round-rimmed). All participants were right-handed, six males and six females, with a median age of 33 and a mean age of 39 ± nine years of standard deviation.

As mentioned in the chapter3, the same twelve participants tested each of the five prototypes over five sessions. Sessions for a given participant were separated by a significant amount of time. The testing order of prototypes was counterbalanced across participants to avoid learning effects as much as possible. The exact session numbers for the haptic joystick's testing are summarised in Table 5.3.

Table 5.3: Participants' session numbers for octagonal-rimmed haptic joystick tests

Participant	Session no.
P1, P2	2nd
P3, P4	2nd
P5, P6	2nd
P7, P8	3rd
P9, P10	4th
P11, P12	5th

Apparatus

Hardware and software items used to test the octagonal-rimmed haptic joystick are listed below:

- Haptic joystick (octagonal-rimmed) (as described in Chapter 3)
- Earmuffs
- Blindfold
- Arduino mega 2560
- Laptop with Unity application, an open-source Unity library called Unity Experiment Framework (UXF), WiinUSoft (3.4) for Windows drivers and XInput wrapper for the Wii controller, and custom C# scripts to interface with the haptic joystick.

Stimuli

In the octagonal-rimmed haptic joystick's case, each stimulus was one of the seven positions along the edges and corners of the octagonal rim representing a specific direction accompanied by a vibration pattern representing near or far proximities. The stimuli, or haptic cues, have been described in detail in chapter3.[20]

Task

[20] Chapter 3, section3.2.2, haptic joysticks

On exposure to each stimulus, the participant had to verbally indicate the perceived direction as their response during part1 of the session, while direction and proximity during part2. Similar to the round-rimmed joystick, in part 1, which was the direction-only scenario, participants' response could be any direction from a set of seven clock-face directions ranging from 9 o'clock to 3 o'clock. And in part2, which was the direction-and-proximity scenario, participants' response had to be near or far proximity in addition to any direction from a set of seven clock-face directions ranging from 9 o'clock to 3 o'clock. Participants were allowed to repeat (re-expose) the exposed stimulus as often as required until they were ready to indicate their response. Furthermore, participants had to fill out two sets of questionnaires (experienced workload and usability) at the end of both parts of the session. Finally, an informal interview was done at the end of the session.

With the above setup, each of the twelve participants tested the haptic joystick (octagonal-rimmed). The task design, data collected, and the procedure followed have been described in detail in Chapter3.[21] The objective and subjective data collected during the testing of the haptic joystick are presented and discussed in the following section.

5.2.2 Results & Discussion

This subsection presents results for the five variables of interest:

- accuracy
- time taken
- repeats taken
- experienced mental workload
- system usability score

The accuracy results are organised into two levels of detail: the stimuli-level and the overall device-level. Stimuli-level results give an insightful summary of the device tested; However, only device-level results are used for statistical comparisons to address relevant research questions. Therefore, device-level overall results are provided for all variables of interest.

Accuracy

[21] Chapter 3, section 3.3, 3.4, 3.5

Figure 5.7 presents a visual summary of the accuracy and precision for each stimulus during part1 (direction-only) and part2 (direction-and-proximity) of the tests. It shows that the accuracy slightly decreased during part2 of the tests – there are more light red coloured blocks along the white diagonal 100% accuracy line.

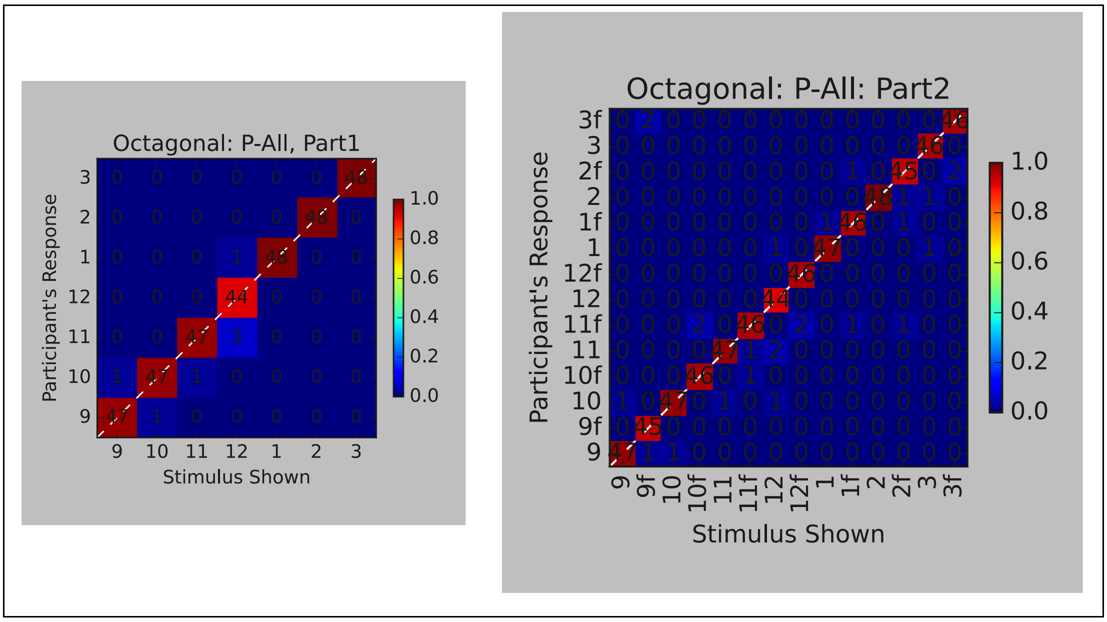

Figure 5.7: Summary of accuracy during direction-only and direction-and-proximity parts of the tests for the octagonal-rimmed joystick: (Left) Response matrix for the direction-only part, (Right) Response matrix direction-and-proximity for part

However, the overall accuracy during each part of the tests is used for comparisons. Therefore, Figure 5.8 shows the mean wristband accuracy during each part of the tests as the bar heights. The red points represent the mean accuracies of the participants. Error bars represent 95% confidence intervals for the mean of the accuracy for each part.

During part 1, mean accuracy was 98% (96, 99), while during part 2, it was 96% (94, 98). This equates to a Cohen's effect size (dz) value of 0.41. The accuracy comparison between part 2 and part 1 using a (matched pairs) t-test shows a lack of significant difference (t=-1.4, p= 0.18). The lack of significant difference suggests that there is no meaningful increase or decrease in the accuracy during part 2 of the tests compared to part 1.

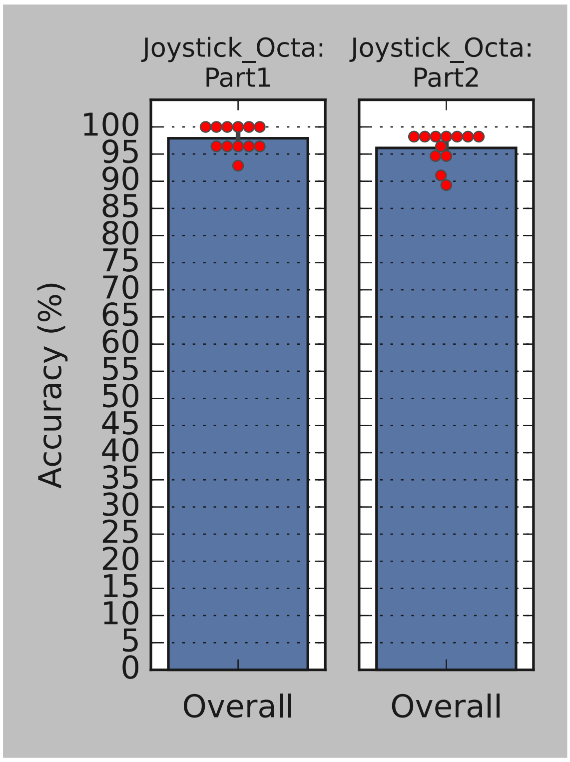

Figure 5.8: Mean accuracy during direction-only and direction-and-proximity parts of the tests for the octagonal-rimmed joystick. Error bars represent the 95% confidence interval for the mean.

Time-taken

Figure 5.9 shows the mean time-taken per trial during each part of the tests as the bar heights. The red points represent the mean time-taken by the participants. Error bars represent 95% confidence intervals for the mean of the time-taken (per trial) for each part.

During part 1, mean time-taken was 7.6 seconds (5.7, 9.5), while during part 2, it was 9.2 seconds (7.0, 11.4). This equates to a Cohen's effect size (dz) value of 1.37. The time-taken comparison between part 2 and part 1 using a (matched pairs) t-test shows a significant difference ($t= 4.8$, $p<0.001$). The significant difference and the large effect size suggest that there is a meaningful increase in the time-taken during part 2 of the tests compared to part 1

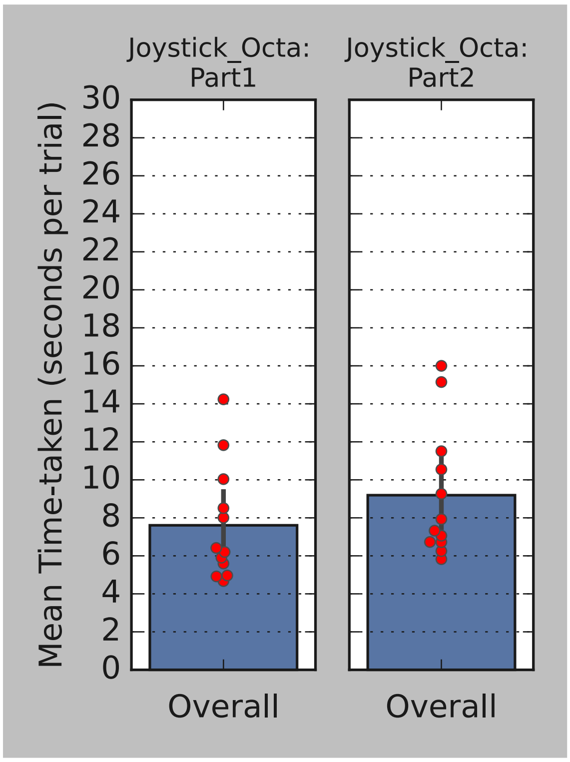

Figure 5.9: Mean time-taken during direction-only and direction-and-proximity parts of the tests for the octagonal-rimmed joystick. Error bars represent the 95% confidence interval for the mean.

Repeats-taken

Figure 5.10 shows the mean number of times a given stimulus was repeated/replayed per trial before the participant reported their response during each part of the tests. The mean repeats-taken per trial for each part is shown by the bar heights. The red points represent the mean number of repeats taken by the participants. Error bars represent 95% confidence intervals for the mean of the repeats-taken (per trial) for each part.

During part 1, mean repeats-taken (per trial) was 1.6 (1, 2), while during part 2, it was 1.4 (1, 2). This equates to a Cohen's effect size (dz) value of 0.43. The repeats-taken comparison between part 2 and part 1 using a (matched pairs) t-test shows a lack of significant difference (t=-1.5, p=0.16). The lack of significant difference suggests that there is no meaningful increase or decrease in the repeats-taken during part 2 of the tests compared to part 1. It shows that participants requested negligible repeats/replays of the stimuli after first exposure during both parts of the tests.

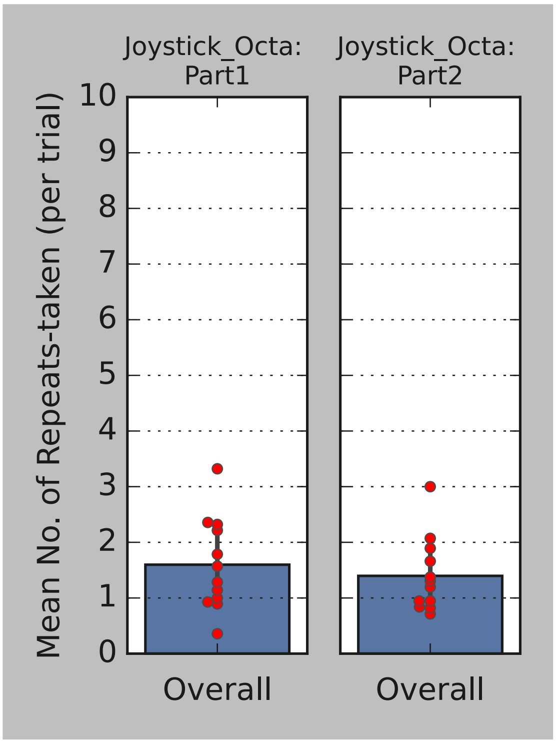

Figure 5.10: Mean number of repeats-taken during direction-only and direction-and-proximity parts of the tests for the octagonal-rimmed joystick. Error bars represent the 95% confidence interval for the mean.

Experienced mental workload

Figure 5.11 shows the mean mental workload experienced by the participants during each part of the tests as the bar heights. The red points represent participants' task load index (TLX) scores. Error bars represent 95% confidence intervals for the mean of the TLX scores for each part.

During part 1, mean mental workload experienced as TLX score was 32 (21, 43), while during part 2, it was 40 (26, 55). This equates to a Cohen's effect size (dz) value of 0.71. The TLX score comparison between part 2 and part 1 using a (matched pairs) t-test shows a significant difference (t=2.4, p=0.03). The significant difference suggest that there is a meaningful increase in experienced mental workload during part 2 of the tests compared to part 1. It shows that participants experienced a higher mental workload during part 2 (direction-and-proximity) of the tests.

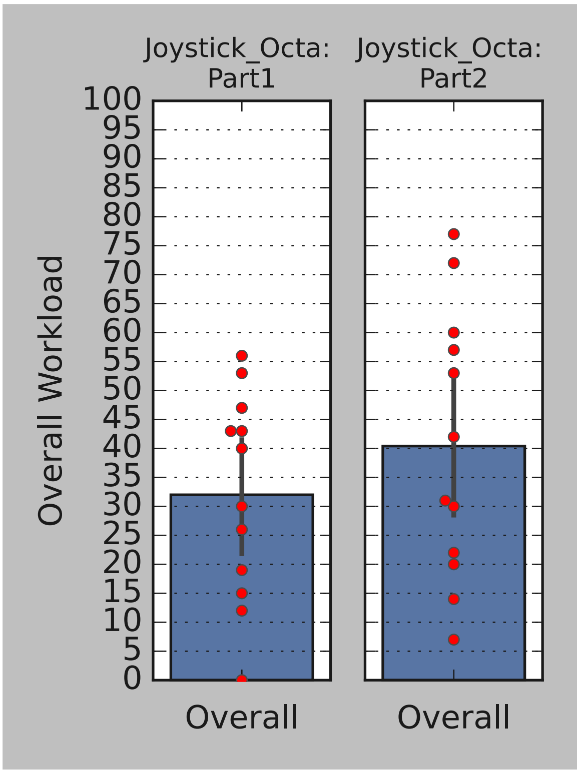

Figure 5.11: Mean task load index score during direction-only and direction-and-proximity parts of the tests for the octagonal-rimmed joystick. Error bars represent the 95% confidence interval for the mean.

System usability score

Figure 5.12 shows the mean System Usability Scale (SUS) score during each part of the tests as bar heights. The red points represent participants' perceived system usability score. Error bars represent 95% confidence intervals for the mean of the SUS scores for each part.

During part 1, mean SUS score was 80 (71, 90), while during part 2, it was 77 (66, 87). This equates to a Cohen's effect size (dz) value of 0.54. The SUS score comparison between part 2 and part 1 using a (matched pairs) t-test shows a lack of significant difference (t=-1.9, p=0.09). The lack of significant difference suggests that there is no meaningful increase or decrease in the perceived usability during part 2 of the tests compared to part 1.

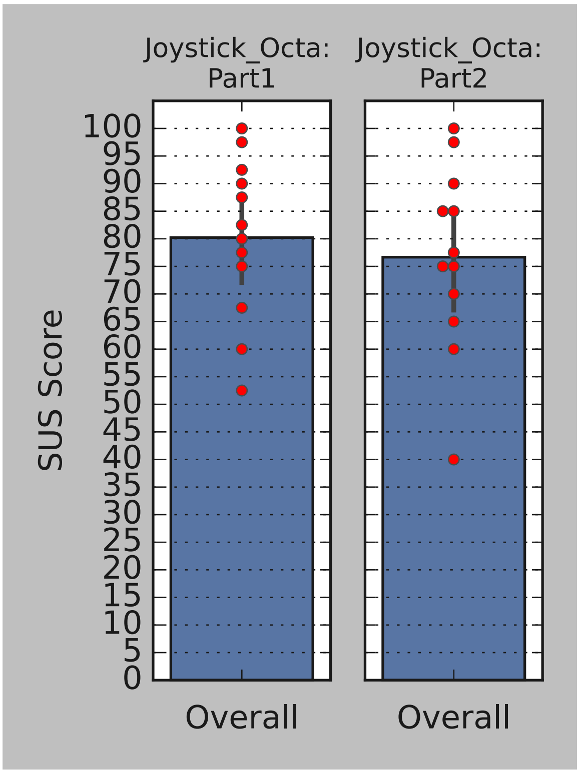

Figure 5.12: Mean System Usability Score (SUS) during direction-only and direction-and-proximity parts of the tests for the octagonal-rimmed joystick. Error bars represent the 95% confidence interval for the mean.

Comparison: Direction-only vs Direction-and-proximity

Table 5.4 presents the results for each variable of interest for the octagonal-rimmed joystick. It compares the performance during part2 to part1. The null hypothesis tested is that there is no difference between the (within-subjects) means during part1 and part2 of the tests. The statistics given are means with 95% confidence intervals for the given means, t-values for observing such a result for the given dependent variable given the null hypothesis is true, the associated likelihood p-value of observing such an effect, and the Cohen's effect size (dz) value. The red circle means a statistically significant decline was detected in the performance for the given variable during part2 relative to part1 of the tests. The yellow equality sign means no statistically significant difference was detected in the performance for the given variable during part2 relative to part1. Finally, the green circle means a statistically significant improvement was detected in the performance for the given variable during part2 relative to part1 of the tests.

Table 5.4: Comparison of with-in subjects' performance between the direction-only and direction-and-proximity parts of the tests for the octagonal-rimmed joystick

Variable of Interest	Joystick_Octa during Part2 (compared to Part1)		Joystick_Octa during Part1
Accuracy	=	96% (t=-1.4, p= 0.18, dz= 0.41)	98%
Time-taken	●	9.2 seconds per trial (t= 4.8, p<0.001, dz=1.37)	7.6 seconds per trial
Repeats-taken	=	1.4 repeats per trial (t=-1.5, p=0.16, dz=0.43)	1.6 repeats per trial
Experienced mental workload	●	40 TLX (t=2.45, p=0.03, dz=0.71)	32 TLX (Score out of 100)
Perceived system-usability	=	77 SUS (t=-1.9, p=0.09, dz=0.54)	80 SUS (Score out of 100)

Translating the results, shown in Table 5.4, into practical significance, the (octagonal-rimmed) haptic joystick's user will take longer per instruction (time-taken) for direction-and-proximity guidance and will find the device more mentally demanding. Therefore, with the given design of the octagonal-rimmed joystick and haptic cues, the device is more intuitive and effective for direction-only guidance than direction-and-proximity guidance.

This section has established another reference point to compare other active proprioceptive devices against. The octagonal-rimmed joystick forms a good example of making a subtle change to the design and detecting its effect on the performance. In the next section, the haptic dial's results are presented - independent of other devices; finally, the last section compares the performance of these active proprioceptive devices tested.

5.3 The Haptic Dial

Dials, similar to joysticks, engage the user's sense of proprioception. They are a widespread component of many human-machine interfaces. Examples range from old rotary telephones to control dials in modern cars. Regarding navigation, compasses have dials with directions labelled on them that navigators turn to estimate their heading. A steering wheel is another good example, essentially an oversized dial that the user turns to control the direction of a vehicle. Can an active proprioceptive device, like a dial, intuitively and effectively display directions for navigation? This section addresses this question using a dial as another design example of an active proprioceptive device.

The subsections below present the experimental setup used to collect data for the objective and subjective measures of the haptic dial. It also presents the results as graphs for each variable of interest, accompanied by a discussion where needed.

5.3.1 Experimental Setup

This subsection describes the experimental setup used for testing the haptic dial. The experimental setup is explained in terms of four aspects: participants, apparatus, stimuli, and task. The explanation should allow replication of the experimental setup.

Participants

Twelve sighted individuals, aged between 23 and 59, tested the haptic dial. All participants were right-handed, six males and six females, with a median age of 33 and a mean age of 39 ± nine years of standard deviation.

As mentioned in the chapter3, the same twelve participants tested each of the five prototypes over five sessions. Sessions for a given participant were separated by a significant amount of time. The testing order of prototypes was counterbalanced across participants to avoid learning effects as much as possible. The exact session numbers for the haptic dial's testing are summarised in Table 5.5.

Table 5.5: Participants' session numbers for haptic dial tests

Participant	Session no.
P1, P2	3rd
P3, P4	3rd
P5, P6	4th
P7, P8	5th
P9, P10	2nd
P11, P12	3rd

Apparatus

Hardware and software items used to test the haptic dial are listed below:

- Haptic dial (as described in Chapter 3)
- Earmuffs
- Blindfold
- Arduino uno r3
- Laptop with Unity application, an open-source Unity library called Unity Experiment Framework (UXF), and custom C# scripts to interface with the haptic belt.

Stimuli

In the haptic dial's case, each stimulus was one of the seven angular positions along the circumference of the dial representing a specific direction accompanied by a vibration pattern representing near or far proximities. The stimuli, or haptic cues, have been described in detail in chapter3.[22]

Task

On exposure to each stimulus, the participant had to verbally indicate the perceived direction as their response during part1 of the session, while direction and proximity during part2. Similar to the joysticks, in part 1, which was the direction-only scenario, participants' response could be any direction from a set of seven clock-face directions ranging from 9 o'clock to 3 o'clock. And in part2,

[22] Chapter 3, section 3.2.2, haptic dial

which was the direction-and-proximity scenario, participants' response had to be near or far proximity in addition to any direction from a set of seven clock-face directions ranging from 9 o'clock to 3 o'clock. Participants were allowed to repeat (re-expose) the exposed stimulus as often as required until they were ready to indicate their response. Furthermore, participants had to fill out two sets of questionnaires (experienced workload and usability) at the end of both parts of the session. Finally, an informal interview was done at the end of the session.

With the above setup, each of the twelve participants tested the haptic dial. The task design, data collected, and the procedure followed have been described in detail in Chapter3.[23] The objective and subjective data collected during the testing of the haptic dial are presented and discussed in the following section.

5.3.2 Results & Discussion

This subsection presents results for the five variables of interest:

- accuracy
- time taken
- repeats taken
- experienced mental workload
- system usability score

The accuracy results are organised into two levels of detail: the stimuli-level and the overall device-level. Stimuli-level results give an insightful summary of the device tested; However, only device-level results are used for statistical comparisons to address relevant research questions. Therefore, device-level overall results are provided for all variables of interest.

Accuracy

Figure 5.13 presents a visual summary of the accuracy and precision for each stimulus during part1 (direction-only) and part2 (direction-and-proximity) of the tests. It shows that the accuracy slightly increased during part2 of the tests. There are more dark red coloured blocks along the white diagonal 100% accuracy line.

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[23] Chapter3, section 3.3, 3.4, 3.5

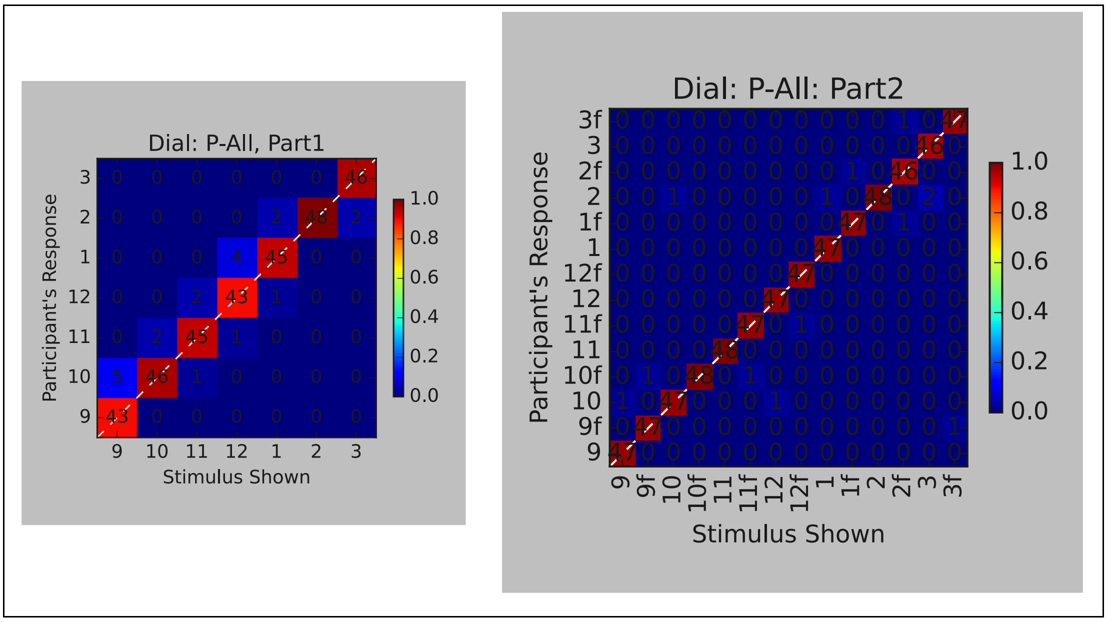

Figure 5.13: Summary of accuracy during direction-only and direction-and-proximity parts of the tests for the haptic dial: (Left) Response matrix for the direction-only part, (Right) Response matrix for direction-and-proximity part

However, the overall accuracy during each part of the tests is used for comparisons. Therefore, Figure 5.14 shows the mean wristband accuracy during each part of the tests as the bar heights. The red points represent the mean accuracies of the participants. Error bars represent 95% confidence intervals for the mean of the accuracy for each part.

During part 1, mean accuracy was 94% (89, 99), while during part 2, it was 98% (96, 100). This equates to a Cohen's effect size (dz) value of 0.52. The accuracy comparison between part 2 and part 1 using a (matched pairs) t-test shows a lack of significant difference (t=1.8, p= 0.11). The lack of significant difference suggests that there is no meaningful increase or decrease in the accuracy during part 2 of the tests compared to part 1.

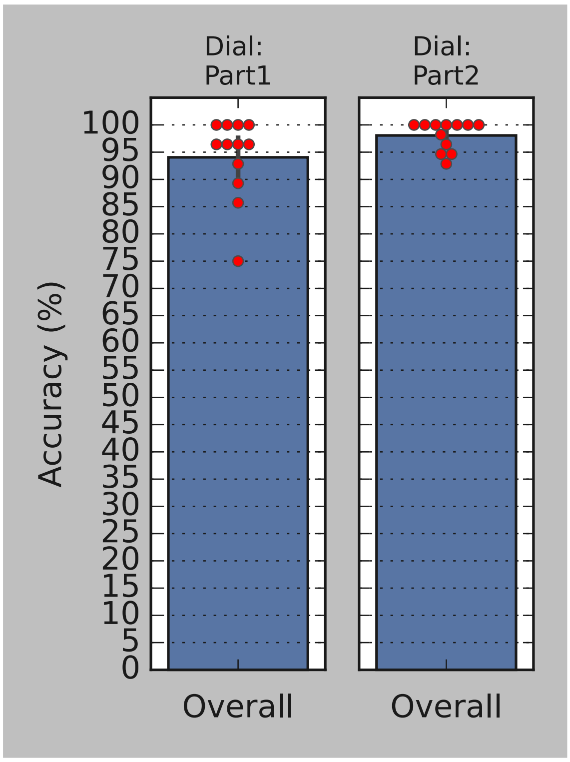

Figure 5.14: Mean accuracy during direction-only and direction-and-proximity parts of the tests for the haptic dial. Error bars represent the 95% confidence interval for the mean.

Time-taken

Figure 5.15 shows the mean time-taken per trial during each part of the tests as the bar heights. The red points represent the mean time-taken by the participants. Error bars represent 95% confidence intervals for the mean of the time-taken (per trial) for each part.

During part 1, mean time-taken was 11.5 seconds (8.1, 14.8), while during part 2, it was 10.4 seconds (8.5, 12.3). This equates to a Cohen's effect size (dz) value of 0.38. The time-taken comparison between part 2 and part 1 using a (matched pairs) t-test shows a lack of significant difference (t=-1.3, p=0.21). The lack of significant difference suggests that there is no meaningful increase or decrease in the time-taken during part 2 of the tests compared to part 1.

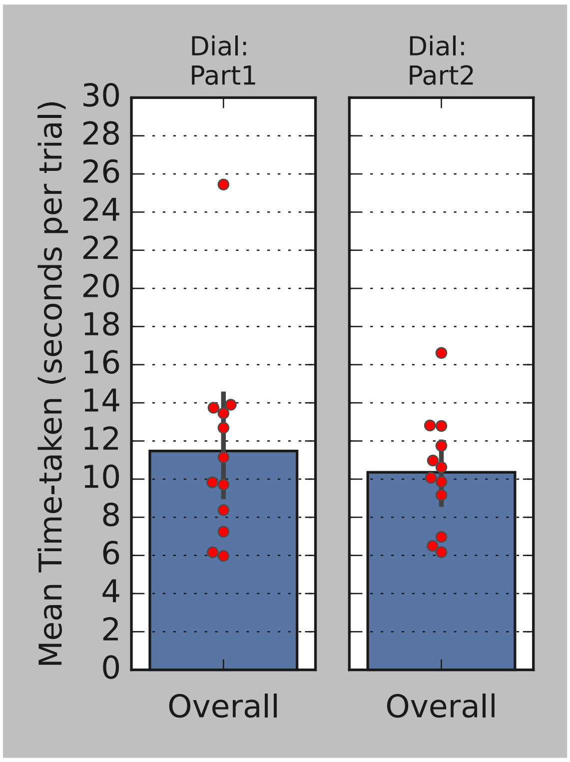

Figure 5.15: Mean time-taken during direction-only and direction-and-proximity parts of the tests for the haptic dial. Error bars represent the 95% confidence interval for the mean.

Repeats-taken

Figure 5.16 shows the mean number of times a given stimulus was repeated/replayed per trial before the participant reported their response during each part of the tests. The mean repeats-taken per trial for each part is shown by the bar heights. The red points represent the mean number of repeats taken by the participants. Error bars represent 95% confidence intervals for the mean of the repeats-taken (per trial) for each part.

During part 1, mean repeats-taken (per trial) was 0.2 (0.05, 0.41), while during part 2, it was 0.2 (0.04, 0.31). This equates to a Cohen's effect size (dz) value of 0.3. The repeats-taken comparison between part 2 and part 1 using a (matched pairs) t-test shows a lack of significant difference (t=-1, p=0.32,). The lack of significant difference suggests that there is no meaningful increase or decrease in the repeats-taken during part 2 of the tests compared to part 1. It shows that participants requested negligible repeats/replays of the stimuli after first exposure during both parts of the tests.

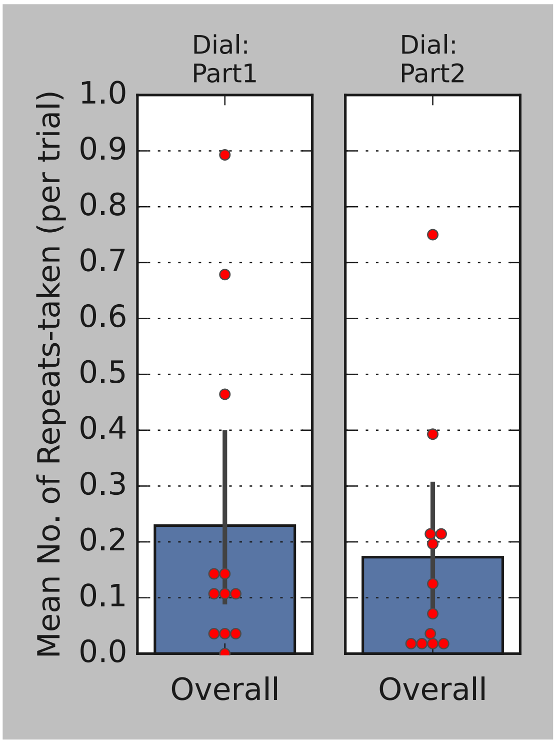

Figure 5.16: Mean number of repeats-taken during direction-only and direction-and-proximity parts of the tests for the haptic dial. Error bars represent the 95% confidence interval for the mean.

Experienced mental workload

Figure 5.17 shows the mean mental workload experienced by the participants during each part of the tests as the bar heights. The red points represent participants' task load index (TLX) scores. Error bars represent 95% confidence intervals for the mean of the TLX scores for each part.

During part 1, mean mental workload experienced as TLX score was 56 (47, 65), while during part 2, it was 59 (46, 72). This equates to a Cohen's effect size (dz) value of 0.19. The TLX score comparison between part 2 and part 1 using a (matched pairs) t-test shows a lack of significant difference (t=0.7, p=0.51). The lack of significant difference suggests that there is no meaningful increase or decrease in the experienced mental workload during part 2 of the tests compared to part 1.

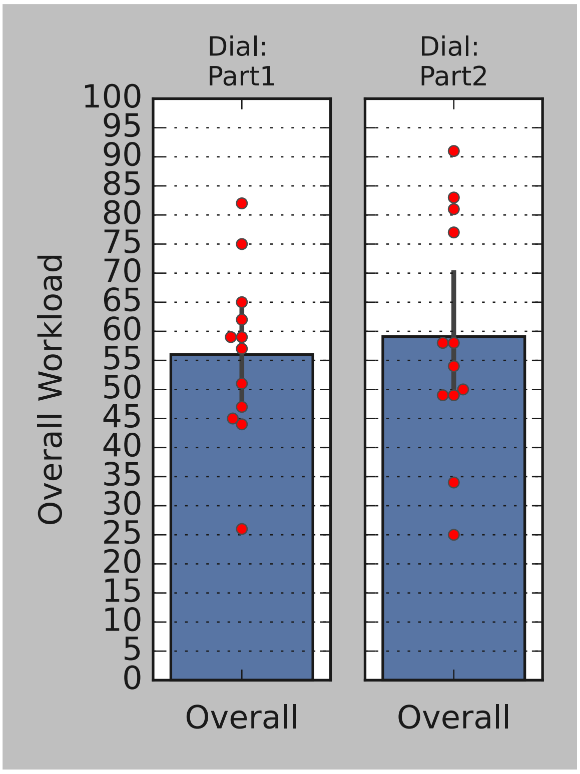

Figure 5.17: Mean task load index score during direction-only and direction-and-proximity parts of the tests for the haptic dial. Error bars represent the 95% confidence interval for the mean.

System usability score

Figure 5.18 shows the mean System Usability Scale (SUS) score during each part of the tests as bar heights. The red points represent participants' perceived system usability score. Error bars represent 95% confidence intervals for the mean of the SUS scores for each part.

During part 1, mean SUS score was 59 (49, 68), while during part 2, it was 59 (48, 71). This equates to a Cohen's effect size (dz) value of 0.04. The SUS score comparison between part 2 and part 1 using a (matched pairs) t-test shows a lack of significant difference (t=0.15, p=0.89). The lack of significant difference suggests that there is no meaningful increase or decrease in the perceived usability during part 2 of the tests compared to part 1.

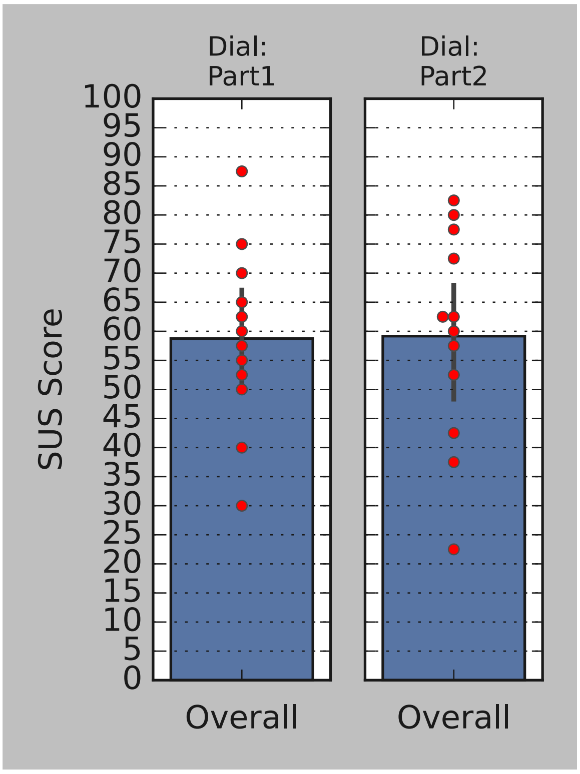

Figure 5.18: Mean System Usability Score (SUS) during direction-only and direction-and-proximity parts of the tests for the haptic dial. Error bars represent the 95% confidence interval for the mean.

Comparison: direction-only vs direction-and-proximity

Table 5.6 presents the haptic dial's results for each variable of interest. It compares the performance during part2 to part1. The null hypothesis tested is that there is no difference between the (within-subjects) means during part1 and part2 of the tests. The statistics given are means with 95% confidence intervals for the given means, t-values for observing such a result for the given dependent variable given the null hypothesis is true, the associated likelihood p-value of observing such an effect, and the Cohen's effect size (dz) value. The red circle means a statistically significant decline was detected in the performance for the given variable during part2 relative to part1 of the tests. The yellow equality sign means no statistically significant difference was detected in the performance for the given variable during part2 relative to part1. Finally, the green circle means a statistically significant improvement was detected in the performance for the given variable during part2 relative to part1 of the tests.

Table 5.6: Comparison of with-in subjects' performance between the direction-only and direction-and-proximity parts of the tests for the haptic dial

Variable of Interest	Dial during Part2 (compared to Part1)		Dial during Part1
Accuracy	=	98% (t=1.8, p= 0.11, dz= 0.52)	94%
Time-taken	=	10.4 seconds per trial (t=-1.3, p=0.21, dz=0.38)	11.5 seconds per trial
Repeats-taken	=	0.2 repeats per trial (t=-1, p=0.32, dz=0.30)	0.2 repeats per trials
Experienced mental workload	=	56 TLX (t=0.7, p=0.51, dz=0.19)	56 TLX (Score out of 100)
Perceived system-usability	=	59 SUS (t=0.15, p=0.89, dz=0.04)	59 SUS (Score out of 100)

Translating the results, shown in Table 5.6, into practical significance, the haptic dial's user, with the given design of the device and haptic cues, will find it as intuitive and effective for direction-only guidance as for direction-and-proximity guidance.

Another reference point has been established in this section to compare with other devices. The haptic dial is a good reference because it involves more active and proprioceptive engagement of the hand to seek direction. The following section of the chapter compares the performance of the three active proprioceptive devices.

5.4 Comparison: Joysticks vs Dial

Previous sections independently present the results of three active proprioceptive prototypes (the two joysticks and the dial). This section compares the results of the three prototypes to address the sub-research question. The sub-research question is “How intuitive and effective is an active proprioceptive vibrotactile device for navigation”. A more detailed version is “How intuitive and effective is a haptic dial compared to a haptic joystick for navigation”. Figure 5.19 shows the sub-research question divided into elements.

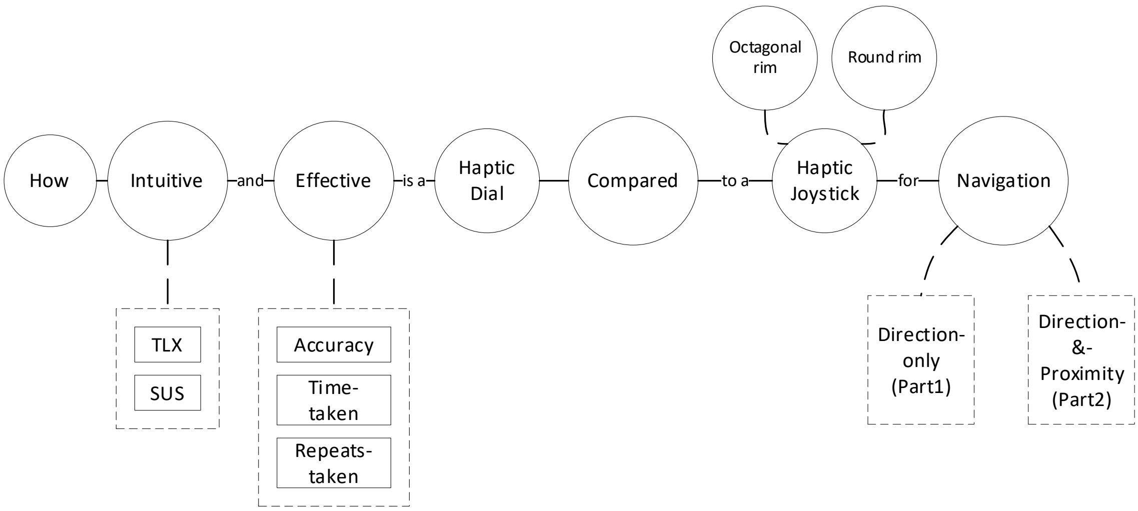

Figure 5.19: Sub-research question for active proprioceptive devices

Table 5.7, Table 5.8, Table 5.9, and Table 5.10 show the comparison results for the given devices during the given scenario: direction-only (part1) and direction-and-proximity (part2). The null hypothesis tested is that there is no difference between the (between-subjects) means of the given devices during the given part of the tests. The statistics given are means with 95% confidence intervals for the given means, t-values for observing such a result for the given dependent variable given the null hypothesis is true, the associated likelihood p-value of observing such an effect, and the Cohen’s effect size (d) value. The red circle means a statistically significant decline was detected in the performance for the given devices and the variable during the given part of the tests. The yellow equality sign means no statistically significant difference was detected in the performance for the given devices and the variable during the given part of the tests. Finally, the green circle means a statistically significant improvement was detected in the performance for the given devices and the variable during the given part of the tests.

Table 5.7: Comparison of the octagonal rim joystick to the round rim joystick during the direction-only part

Variable of Interest	Joystick_Octagonal (compared to Joystick_Round)		Joystick_ Round
Accuracy	●	98% (t=4.83, p<0.001, d= 1.96)	77%
Time-taken	=	7.6 seconds per trial (t=-0.86, p=0.39, d=0.35)	9.2 seconds per trial
Repeats-taken	●	1.6 repeats per trial (t=-2.38, p=0.03, d=0.97)	2.8 repeats per trial
Experienced mental workload	●	32 TLX (t=-2.43, p=0.02, d=0.99, Power=0.64)	50 TLX (Score out of 100)
Perceived system-usability	=	80 SUS (t=1.9, p=0.07, d=0.78)	66 SUS (Score out of 100)

Translating the results, shown in Table 5.7, into practical significance, the (octagonal-rimmed) haptic joystick's user will take fewer instructions (accuracy) and the same amount of time (time-taken) while finding the device less mentally demanding for direction-only guidance. Therefore, with the given design of the octagonal-rimmed joystick and haptic cues, the device is more intuitive and effective for direction-only guidance than the round-rimmed joystick.

Table 5.8: Comparison of the octagonal rim joystick to the round rim joystick during the direction-and-proximity part

Variable of Interest	Joystick_Octagonal (compared to Joystick_Round)		Joystick_ Round
Accuracy	●	96% (t= 3.58, p= 0.002, d= 1.47)	85%

Time-taken	=	9.2 seconds per trial (t= -0.75, p= 0.46, d= 0.31)	10 seconds per trial
Repeats-taken	●	1.4 repeats per trial (t= -2.3, p=0.03, d= 0.94)	2.5 repeats per trial
Experienced mental workload	●	40 TLX (t= -2.07, p= 0.05, d= 0.85)	60 TLX (Score out of 100)
Perceived system-usability	●	77 SUS (t= 2.3, p= 0.03, d= 0.94)	58 SUS (Score out of 100)

Translating the results, shown in Table 5.8, into practical significance, the (octagonal-rimmed) haptic joystick's user will take fewer instructions (accuracy) and the same amount of time (time-taken) while finding the device less mentally demanding and more usable for direction-and-proximity guidance. Therefore, with the given design of the octagonal-rimmed joystick and haptic cues, the device is more intuitive and effective for direction-and-proximity guidance than the round-rimmed joystick.

Table 5.9: Comparison of the dial to the octagonal rim joystick during the direction-only part

Variable of Interest	Dial (compared to Joystick_Octagonal)		Joystick_ Octagonal
Accuracy	=	94% (t= -1.7, p= 0.10, d= 0.7)	98%
Time-taken	●	11.5 seconds per trial (t=2.2, p=0.04, d=0.9)	7.6 seconds per trial
Repeats-taken	●	0.2 repeats per trial (t= -5.3, p<0.001, d=2.2)	1.6 repeats per trial

Experienced mental workload	🔴	56 TLX (t= 3.6, p= 0.002, d=1.46)	32 TLX (Score out of 100)
Perceived system-usability	🔴	59 SUS (t= -3.5, p= 0.002, d=1.43)	80 SUS (Score out of 100)

Translating the results, shown in Table 5.9, into practical significance, the haptic dial's user will take the same amount of instructions (accuracy) but more time per instruction (time-taken) for direction-only guidance compared to an octagonal joystick. More time taken per instruction will lead to a longer accumulative time to navigate with the dial. The user will find the dial more mentally demanding and less usable for direction-only guidance than an octagonal joystick. Therefore, with the given design of the two devices and the haptic cues, the octagonal joystick is more intuitive and effective for direction-only guidance than the haptic dial.

Table 5.10: Comparison of the dial to the octagonal rim joystick during the direction-and-proximity part

Variable of Interest	Dial (compared to Joystick_Octagonal)		Joystick_ Octagonal
Accuracy	=	98% (t= 1.6, p= 0.12, d= 0.66)	96%
Time-taken	=	10.4 seconds per trial (t=0.9, p= 0.39, d=0.36)	9.2 seconds per trial
Repeats-taken	🟢	0.2 repeats per trial (t= -6, p<0.001, d=2.5)	1.4 repeats per trial
Experienced mental workload	🔴	59 TLX (t= 2.1, p= 0.05, d=0.86)	40 TLX (Score out of 100)
Perceived system-usability	🔴	59 SUS (t= -2.4, p= 0.02, d=1)	77 SUS (Score out of 100)

Translating the results, shown in Table 5.10, into practical significance, the haptic dial's user will take the same amount of instructions (accuracy) and time per instruction (time-taken) for direction-and-proximity guidance compared to an octagonal joystick while finding the dial more mentally demanding and less usable than an octagonal joystick. Therefore, with the given design of the two devices and the haptic cues, the octagonal joystick is more intuitive and effective for direction-and-proximity guidance than the haptic dial.

5.5 Findings based on the Interviews

As mentioned in Chapter 3, each session ended with an informal interview to collect participants' experience-based qualitative data. As a recap, questions were mostly open-ended, a few examples are as follows:

- What do they think about this prototype?
- What did they like about the prototype?
- What did they dislike about the prototype?
- How would they rank the prototypes so far tested?

This section presents the key findings from the analysis of the notes that were made during the interviews.

5.5.1 Haptic Joystick (Round rim)

The recurring patterns of comments and issues per the participants, along with the number of participants who notified each pattern are listed below:

- Difficulty in finding directions: Several participants (at least 9) mentioned struggling to find directions; especially the participants who had tested the octagonal-rimmed joystick in a previous session before testing the round-rimmed missed having notches or physical cues.
- Mode preference: Some participants (at least 3) preferred the active mode while some (at least 2) preferred the passive mode.
- Confusion with specific directions: Several participants (at least 7) often expressed confusion or difficulty with specific directions: 10, 11, 12, and 1.
- Ergonomics and preference: Some participants (at least 2), who had tested the octagonal-rimmed joystick in a previous session before testing the round-rimmed joystick, mentioned their preference for the octagonal-

rimmed joystick based on ergonomics and ease of use. While some participants (at least 3) preferred the round-rimmed joystick based on ergonomics.

- Mental demand and frustration: A few participants (at least 3), mentioned feeling mentally taxed and frustrated during the tests.
- One-off comments: There were some one-off comments made by the participants. For example, the pulsation gaps for proximity were too long, leading to frustration, the device made them feel sleepy because of the high mental load, their thumb started aching, and felt they had to point it straight and found it difficult to do so.

Participants also made suggestions for improving the prototype and haptic cues' design. General themes of suggestions are given below:

- Direction/Orientation: All participants mentioned the importance of notches, especially at 9, 12, and 3.
- Clicking: Some participants (at least 2) suggested the use of clicks as a helpful haptic feature to improve direction recognition.
- One-off suggestions: There were some one-off suggestions made by the participants. For example, improving the frequency of pulsation for proximity, the start of vibration as the stick comes closer to the correct direction, and adding dead ends at directions 9 and 3.

5.5.2 Haptic Joystick (Octagonal rim)

The recurring patterns of comments and issues per the participants, along with the number of participants who notified each pattern are listed below:

- Confusion with direction: Participants (at least 3) mentioned confusion with certain directions: 10, 11, and particularly direction 2 o'clock.
- Notches: Some participants (at least 4) mentioned having notches made it easier to recognise directions.
- Ease of use with practice: Some participants (at least 2) found it easy to use once they got used to it.
- Mode preference: Participants (at least 2) expressed a preference for active control, while some (at least 3) preferred passive mode.
- Pulsation preference: Several participants (at least 6) preferred pulsation for proximity, while some (at least 3) preferred it to be a difference in intensity to indicate proximity (like in the case of the belt and wristband). Intensity advocates argued that perception of intensity is instantaneous,

while with pulsation there was a wait involved to confirm if it was a pulse (far) rather than a continuous vibration (near).

- One-off comments: There were some one-off comments made by the participants. For example, the joystick felt small and would be tiring for longer use, pulsation frequency was slow, was more complex than the belt, determining near and far was confusing, direction-only was easier and adding proximity made it difficult and mentally demanding.

Participants also made suggestions for improving the prototype and haptic cues' design. General themes of suggestions are given below:

- Notch Preference: Participants (at least 3) expressed a preference for having "one notch per direction".
- Faster Frequency: Participants (at least 3) suggested a faster frequency.
- Dead ends: Participants (at least 2) suggested adding dead ends at directions 9 and 3.
- One-off suggestions: There were some one-off suggestions made by the participants. For example, using both pulse and intensity together to indicate distance, adding guides and markers similar to dial, and making notches into slots (e.g., cars' gear lever).

5.5.3 Haptic Dial

The recurring patterns of comments and issues per the participants, along with the number of participants who notified each pattern are listed below:

- Effectiveness of markers/guides: Participants (at least 3) found the marker/ guides useful for determining direction.
- Use of pulsation for proximity: Participants (at least 5) found pulsation for proximity to be helpful.
- Difficulty with the two-handed operation: Many participants used both hands, one to hold the device and the other to turn the dial. Some participants (at least 2) found it challenging or inconvenient to use both hands for the direction-finding.
- Mode preference: Participants (at least 3) expressed a preference for active mode and some (at least 2) for passive mode.
- Variation in difficulty by direction: Certain directions were perceived as more difficult (directions: 10, 11, 1, and 2) or easier (directions: 9, 12, and 3) to determine than others.

- Mental demand: A few participants (at least 4) reported an experience of high mental effort to use the dial for determining directions and proximity.
- One-off comments: There were some one-off comments made by the participants. For example, the dial was enjoyable using it was like radar scanning, there should be one click per direction and in-between clicks were confusing, and lack of dead ends or constraints to stop the dial from turning past directions 9 and 3.

Participants also made suggestions for improving the prototype and haptic cues' design. General themes of suggestions are given below:

- Dial Design: Several participants (at least 5) suggested one click per direction on the dial for clarity and ease of use. And several suggested (at least 5) a bigger dial with a more prominent dial notch.
- Dead Ends/Constraints: Several participants (at least 5) suggested dead ends or constraints at 9 and 3 o'clock to keep stop the dial from turning past them.
- Vibration/Intensity: Some participants (at least 3) suggested different vibrations or intensity levels for left and right directions (left directions: 9, 10, and 11; right directions: 1, 2, and 3).
- One-off suggestions: There were some one-off suggestions made by the participants. For example, printing numbers as markers/ guides on the device, using a higher frequency pulsation for proximity, and having hot and cold regions around the target direction meaning the start of vibration as the stick comes closer to the correct direction.

5.6 Conclusion

The octagonal-rimmed joystick was more intuitive (experienced workload) and effective (accuracy), as a navigation display for direction-only and direction-and-proximity guidance, than the round-rimmed joystick.

The octagonal-rimmed joystick was more intuitive (experienced workload and usability) and effective (time-taken), as a navigation display for direction-only guidance, than the haptic dial.

The octagonal-rimmed joystick was more intuitive (experienced workload and usability), as a navigation display for direction-and-proximity guidance, than the haptic dial.

The octagonal-rimmed joystick was as effective (accuracy and time-taken), as a navigation display for direction-and-proximity guidance, as the haptic dial.

The findings from the interview data point towards interesting observations to keep in mind, improvements to make, and issues to solve during future research projects.

Chapter 6

Comparisons: Effectiveness and Intuitiveness

This chapter compares the effectiveness and intuitiveness of each device tested:

- The wristband: a passive single-element-vibrotactile device
- The belt: a passive multi-element-vibrotactile device
- The round joystick: an active single-element-proprioceptive-vibrotactile device (without external tactical cues – round-rimmed)
- The octagonal joystick: an active single-element-proprioceptive-vibrotactile device (with external tactical cues – octagonal-rimmed)
- The dial: an active single-element-proprioceptive-vibrotactile device (with physical tactical cues)

The effectiveness and intuitiveness, as defined in Chapter 3, of each device as a navigational haptic display equates to performance in five aspects:

- Accuracy
- Time-taken
- Repeats-taken
- Overall workload
- System usability

This chapter has six sections, one for quantitative analysis of each variable of interest and the last for presenting the qualitative findings which are based on the informal interviews. Each quantitative section compares the performance of the given aspect across all the devices using one-way Analysis of Variance (ANOVA) and Tukey's Honestly Significant Difference (HSD) test to address the main research question[24]. Finally, the chapter ends with conclusions.

6.1 Accuracy

This section compares the results for accuracy across all the devices.

Firstly, the section presents, for each device, the mean accuracy during the direction-only scenario (part1) and direction-and-proximity scenario (part2). After that, the section presents the results of a one-way ANOVA test for

[24] Main-research-question: how intuitive and effective is an active proprioceptive vibrotactile device compared to a passive vibrotactile device for navigation?

accuracy. And finally, the section presents the results of a Tukey's HSD test for Accuracy.

Figure 6.1 consists of two subplots; subplot-a shows mean accuracy during the direction-only part of the test and subplot-b shows mean accuracy during the direction-and-proximity part of the test.

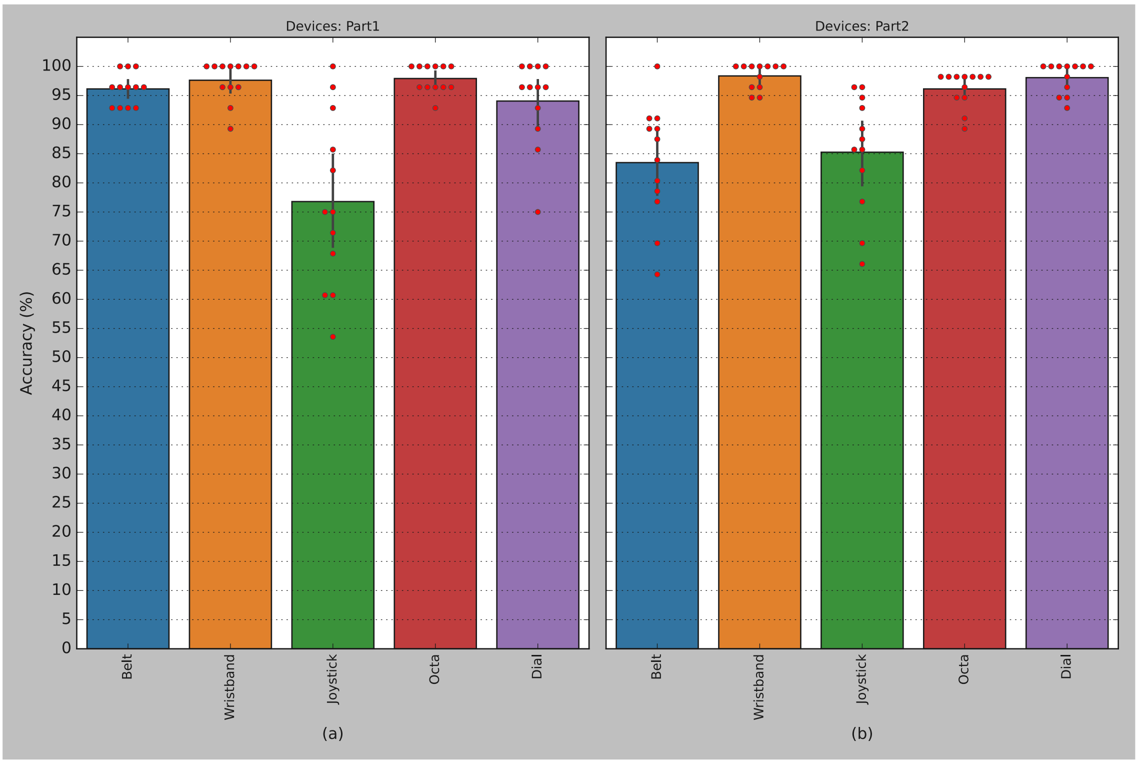

Figure 6.1 Visualisation of the means for accuracy during direction-only and direction-and-proximity parts. Error bars represent the 95% confidence interval for the mean.

Table 6.1 Mean results of accuracy during direction-only and direction-and-proximity parts

Device	Best point estimate: Mean accuracy (Part1) (a)	Best point estimate: Mean accuracy (Part2) (b)
Belt	96.1	83.5
Wristband	97.6	98.4
Round Joystick	76.8	85.3
Octagonal Joystick	97.9	96.1
Dial	94.0	98.1

Figure 6.1(a) and Table 6.1(a) show performance during the direction-only (Part1) scenario. It shows that the round joystick (proprioceptive-single-element-vibrotactile device) was less accurate than other devices, while the wristband (single-element-vibrotactile device) was one of the highest-scoring prototypes in terms of mean accuracy. However, the Octagonal Joystick (proprioceptive, single-element, vibrotactile device with external tactile cues in the form of an octagonal rim/ contour) was the highest-scoring device for mean accuracy.

Figure 6.1(b) and Table 6.1(b) show performance during the direction-and-proximity (Part2) scenario. It shows even though part2 of the test introduced new stimuli for proximity, the round-rimmed joystick showed a statistically significant ($p<0.001$) positive change in performance. In contrast, the belt showed a statistically significant ($p<0.001$) negative change during part2 of the test.

Performing an overall ANOVA test for the accuracy variable-of-interest confirmed statistical differences ($F=16.4$, $p<0.001$) among the devices. Therefore, next, each part/scenario will be tested separately.

For part1, the ANOVA test confirmed statistical differences ($F= 15.6$, $p<0.001$) among the devices. Tukey's HSD post-hoc test results, summarised in Table 6.2, show no significant difference in terms of accuracy across the belt, wristband, octagonal joystick, and dial. In addition, Figure 6.2 shows any significant differences among devices with respect to the belt. It shows that the round joystick was significantly less accurate than the belt, wristband, octagonal joystick, and dial.

Table 6.2 Tukey's HSD results for mean accuracy during the direction-only part

Multiple Comparison of Means – Tukey HSD, FWER=0.05						
group1	group2	Mean diff.	p-adj.	lower	upper	reject H0
Belt	Dial	-2.0833	0.9656	-11.0954	6.9287	FALSE
Belt	Joystick	-19.3452	<.001	-28.3573	-10.3332	TRUE
Belt	JoystickOctagon	1.7857	0.9804	-7.2263	10.7978	FALSE
Belt	Wristband	1.4881	0.9901	-7.524	10.5001	FALSE
Dial	Joystick	-17.2619	<.001	-26.274	-8.2499	TRUE
Dial	JoystickOctagon	3.869	0.7451	-5.143	12.8811	FALSE
Dial	Wristband	3.5714	0.7965	-5.4406	12.5835	FALSE
Joystick	JoystickOctagon	21.131	<.001	12.1189	30.143	TRUE
Joystick	Wristband	20.8333	<.001	11.8213	29.8454	TRUE
JoystickOctagon	Wristband	-0.2976	1	-9.3097	8.7144	FALSE

Notes:
Highlighted rows are the comparisons where the means of the devices are significantly different from each other. Family Wise Error Rate (FWER). Null hypothesis (H0): There is no difference in means; Reject H0 value TRUE means reject the null hypothesis.

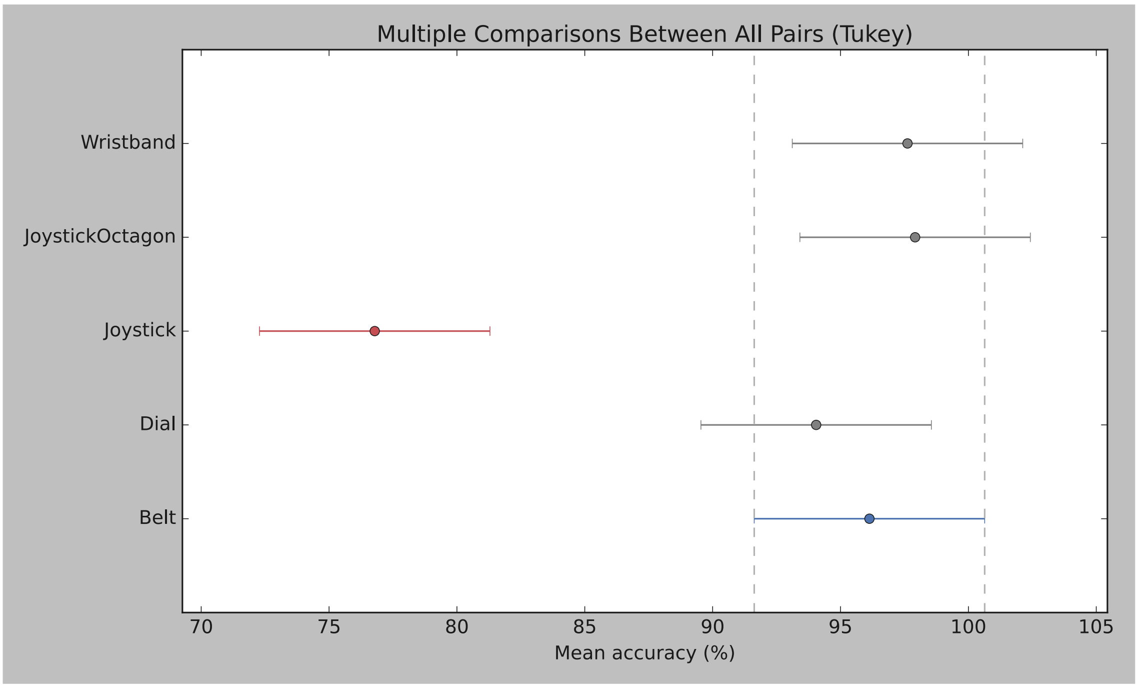

Figure 6.2 Visualisation of Tukey's HSD results for mean accuracy during the direction-only part with respect to the belt. Error bars represent the 95% confidence interval for the mean.

For part2, the ANOVA test confirmed statistical differences (F= 14.2, $p<0.001$) among the devices. Tukey's HSD post-hoc test results, summarised in Table 6.3, show no significant differences in terms of accuracy across the wristband, octagonal joystick, and dial. In addition, Figure 6.3 shows the significant differences, if any, among devices with respect to the belt. It shows that the belt and round joystick were significantly less accurate than the wristband, octagonal joystick, and dial.

Table 6.3 Tukey's HSD results for mean accuracy during the direction-and-proximity part

Multiple Comparison of Means – Tukey HSD, FWER=0.05						
group1	group2	Mean diff.	p-adj.	lower	upper	Reject H0
Belt	Dial	14.5833	<0.001	6.8803	22.2864	TRUE

Belt	Joystick	1.7857	0.9652	-5.9173	9.4888	FALSE
Belt	JoystickOctagon	12.6488	0.0002	4.9458	20.3519	TRUE
Belt	Wristband	14.881	<0.001	7.1779	22.584	TRUE
Dial	Joystick	-12.7976	0.0002	-20.5007	-5.0946	TRUE
Dial	JoystickOctagon	-1.9345	0.9537	-9.6376	5.7685	FALSE
Dial	Wristband	0.2976	1	-7.4054	8.0007	FALSE
Joystick	JoystickOctagon	10.8631	0.0019	3.16	18.5662	TRUE
Joystick	Wristband	13.0952	0.0001	5.3922	20.7983	TRUE
JoystickOctagon	Wristband	2.2321	0.9242	-5.4709	9.9352	FALSE

Notes:
Highlighted rows are the comparisons where the means of the devices are significantly different from each other.
Family Wise Error Rate (FWER).
Null hypothesis (H0): There is no difference in means; Reject H0 value TRUE means reject the null hypothesis.

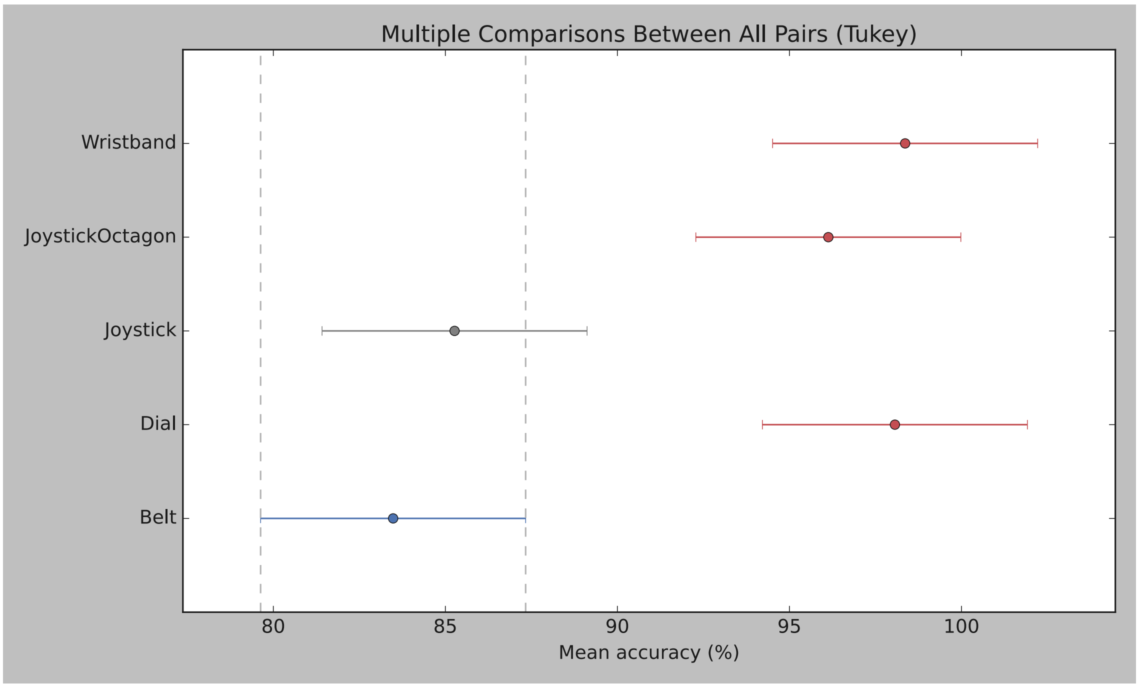

Figure 6.3 Visualisation of Tukey's HSD results for mean accuracy during the direction-and-proximity part with respect to the belt. Error bars represent the 95% confidence interval for the mean.

To conclude this section, the results show that for direction-only instructions active proprioceptive-vibrotactile devices are as accurate or less (in the case of the joystick) as passive-vibrotactile devices, whereas for direction-and-proximity instructions active devices' performance was unchanged, however, belt's performance decreased noticeably.

The following section presents the performance of each device in terms of time taken per stimulus.

6.2 Time-taken

This section compares the results for time-taken per trial across all the devices.

Firstly, the section presents, for each device, the mean time-taken during the direction-only scenario (part1) and direction-and-proximity scenario (part2). After that, the section presents the results of a one-way ANOVA test for time taken. And finally, the section presents the results of Tukey's HSD test for the time taken.

Figure 6.4 consists of two subplots; subplot-a shows mean time-taken during the direction-only part of the test and subplot-b shows mean time-taken during the direction-and-proximity part of the test.

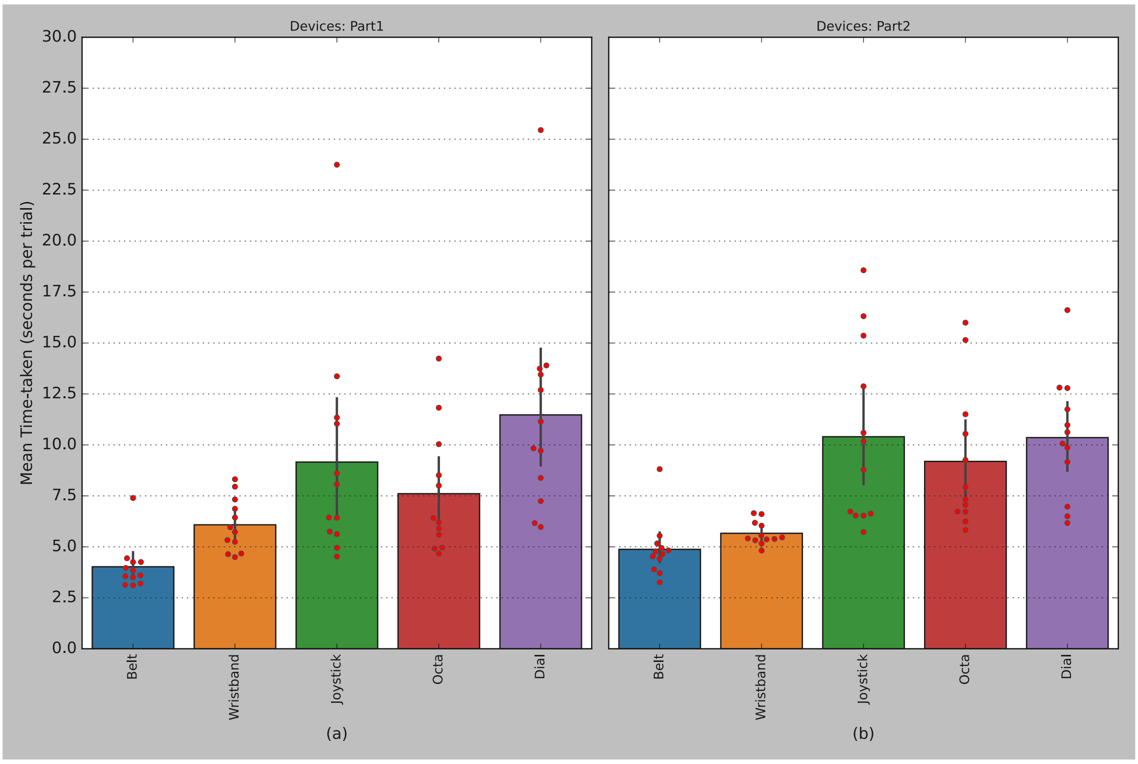

Figure 6.4 Visualisation of the means for the time taken per trial during direction-only and direction-and-proximity parts. Error bars represent the 95% confidence interval for the mean.

Table 6.4 Mean results of time-taken during direction-only and direction-and-proximity parts

Device	Best point estimate: Mean time-taken (Part1) (a)	Best point estimate: Mean time-taken (Part2) (b)
Belt	4	4.9
Wristband	6.1	5.7
Joystick	9.2	10.4
JoystickOctagon	7.6	9.2
Dial	11.5	10.4

Figure 6.4(a) and Table 6.4(a) show performance during the direction-only (Part1) scenario. It shows that the dial (active proprioceptive device with external tactile cues) took significantly more time per trial than other devices during the direction-only scenario. The wristband and belt (passive devices) had a significantly better time performance than the round joystick, octagonal joystick, and dial (active devices).

Figure 6.4(b) and Table 6.4(b) show performance during the direction-and-proximity (Part2) scenario. It shows that the active devices again took significantly more time per trial than the passive devices. The active devices took around 10 seconds per trial, while the passive device took five seconds per trial.

Performing an overall ANOVA test for the time-taken variable-of-interest confirmed statistical differences ($F=9.0$, $p<0.001$) among the devices. Therefore, next, each part/scenario will be tested separately.

For part1, the ANOVA test confirmed statistical differences ($F= 7.1$, $p<0.001$) among the devices. Tukey's HSD post-hoc test results, summarised in Table 6.5, show significant differences in the time taken per trial across devices. In addition, Figure 6.5 shows, if any, significant differences among devices with respect to the belt. The belt and wristband (passive vibrotactile devices) took significantly less time per trial than the joystick, octagonal joystick, and dial (the active proprioceptive devices). The belt was the best-performing device, while the dial was the lowest.

Table 6.5 Tukey HSD results for mean time-taken during the Direction-only part

Multiple Comparison of Means – Tukey HSD, FWER=0.05

group1	group2	Mean diff.	p-adj.	lower	upper	Reject H0
Belt	Dial	7.4512	0.0001	3.1795	11.723	TRUE
Belt	Joystick	5.1358	0.0109	0.8641	9.4076	TRUE
Belt	JoystickOctagon	3.5846	0.1401	-0.6871	7.8564	FALSE
Belt	Wristband	2.0587	0.6558	-2.2131	6.3304	FALSE
Dial	Joystick	-2.3154	0.5487	-6.5872	1.9563	FALSE
Dial	JoystickOctagon	-3.8666	0.0938	-8.1384	0.4051	FALSE
Dial	Wristband	-5.3926	0.0067	-9.6643	-1.1208	TRUE
Joystick	JoystickOctagon	-1.5512	0.8431	-5.823	2.7205	FALSE
Joystick	Wristband	-3.0772	0.2649	-7.3489	1.1946	FALSE
JoystickOctagon	Wristband	-1.5259	0.8508	-5.7977	2.7458	FALSE

Notes:
Highlighted rows are the comparisons where the means of the devices are significantly different from each other.
Family Wise Error Rate (FWER).
Null hypothesis (H0): There is no difference in means; Reject H0 value TRUE means rejecting the null hypothesis.

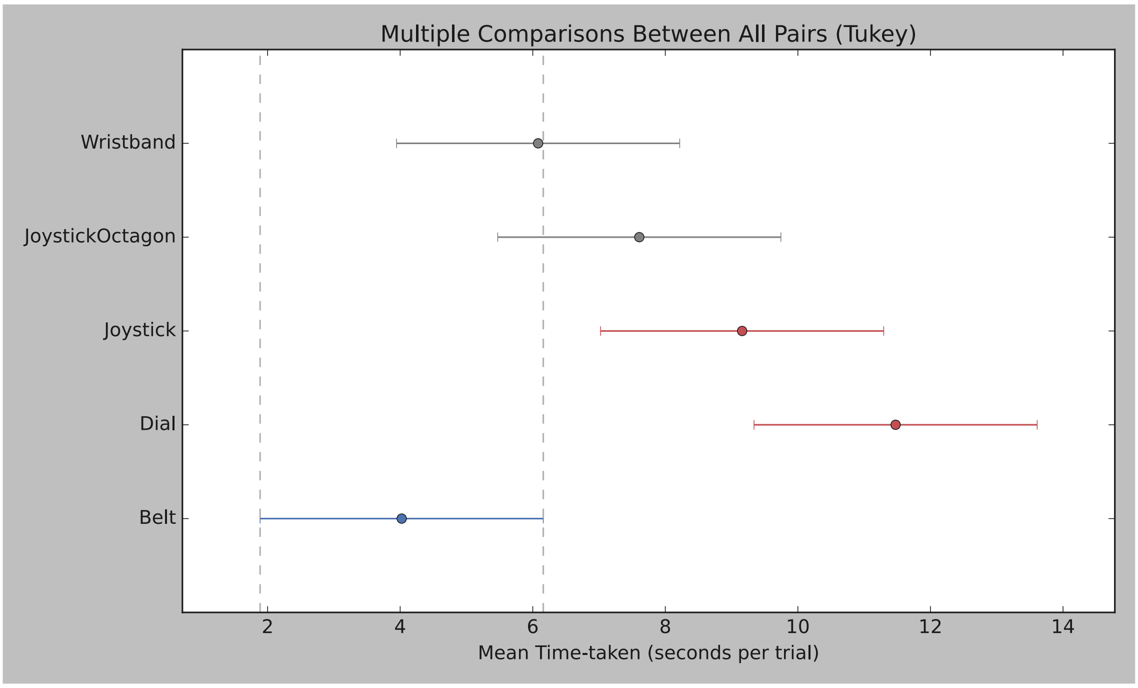

Figure 6.5 Visualisation of Tukey HSD results for mean time-taken during the direction-only part with respect to the belt. Error bars represent the 95% confidence interval for the mean.

For part2, the ANOVA test confirmed statistical differences ($F= 9.8$, $p<0.001$) among the devices. Tukey's HSD post-hoc test results, summarised in Table 6.6, show significant differences in the time taken per trial across all devices. In addition, Figure 6.6 shows any significant differences among devices with respect to the belt. The belt and wristband (passive vibrotactile devices) took significantly less time per trial than the joystick, octagonal joystick, and dial (the active proprioceptive devices). The belt was the best-performing device, while the round joystick was the lowest.

Table 6.6 Tukey HSD results for mean time-taken during the direction-and-proximity part

Multiple Comparison of Means – Tukey HSD, FWER=0.05						
group1	group2	Mean diff.	p-adj.	lower	upper	Reject H0
Belt	Dial	5.4808	0.0002	2.117	8.8445	TRUE
Belt	Joystick	5.5252	0.0002	2.1614	8.889	TRUE
Belt	JoystickOctagon	4.3144	0.0056	0.9507	7.6782	TRUE
Belt	Wristband	0.7876	0.9639	-2.5761	4.1514	FALSE
Dial	Joystick	0.0444	1	-3.3193	3.4082	FALSE
Dial	JoystickOctagon	-1.1663	0.864	-4.5301	2.1975	FALSE
Dial	Wristband	-4.6931	0.0021	-8.0569	-1.3293	TRUE
Joystick	JoystickOctagon	-1.2108	0.8473	-4.5745	2.153	FALSE
Joystick	Wristband	-4.7376	0.0019	-8.1013	-1.3738	TRUE
JoystickOctagon	Wristband	-3.5268	0.0355	-6.8906	-0.163	TRUE

Notes:
Highlighted rows are the comparisons where the means of the devices are significantly different from each other.
Family Wise Error Rate (FWER).
Null hypothesis (H0): There is no difference in means; Reject H0 value TRUE means rejecting the null hypothesis.

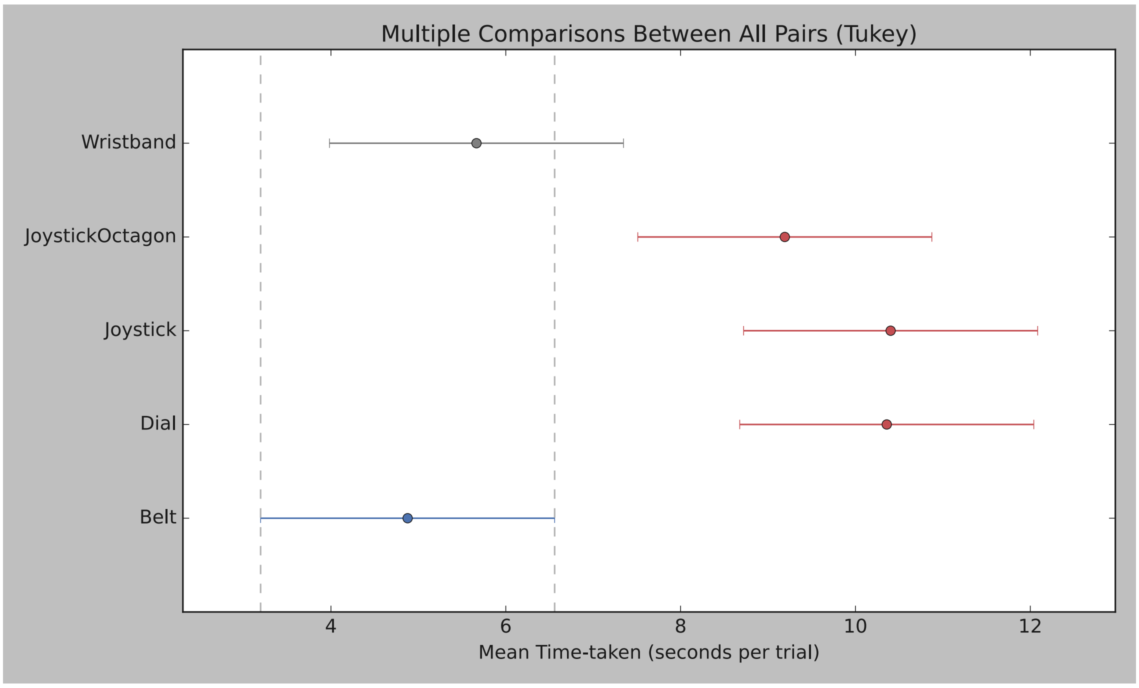

Figure 6.6 Visualisation of Tukey HSD results for mean time-taken during the direction-only part with respect to the belt. Error bars represent the 95% confidence interval for the mean.

To conclude this section, the results show that for direction-only instructions the active proprioceptive-vibrotactile devices require the same (in the case of the octagonal joystick) or more time per instruction than the passive vibrotactile devices, whereas for direction-and-proximity instructions active devices required more time per instruction.

The following section presents the effectiveness of each device in terms number of repeats taken per trial.

6.3 Repeats-taken

This section compares the mean number of repeats taken per trial across all the devices.

Firstly, the section presents, for each device, the mean number of repeats taken during the direction-only scenario (part1) and direction-and-proximity scenario (part2). After that, the section presents the results of a one-way ANOVA test for number of repeats taken. And finally, the section presents the results of a Tukey's HSD test for repeats-taken.

Figure 6.7 consists of two subplots; subplot-a shows mean repeats-taken during the direction-only part of the test and subplot-b shows mean repeats-taken during the direction-and-proximity part of the test.

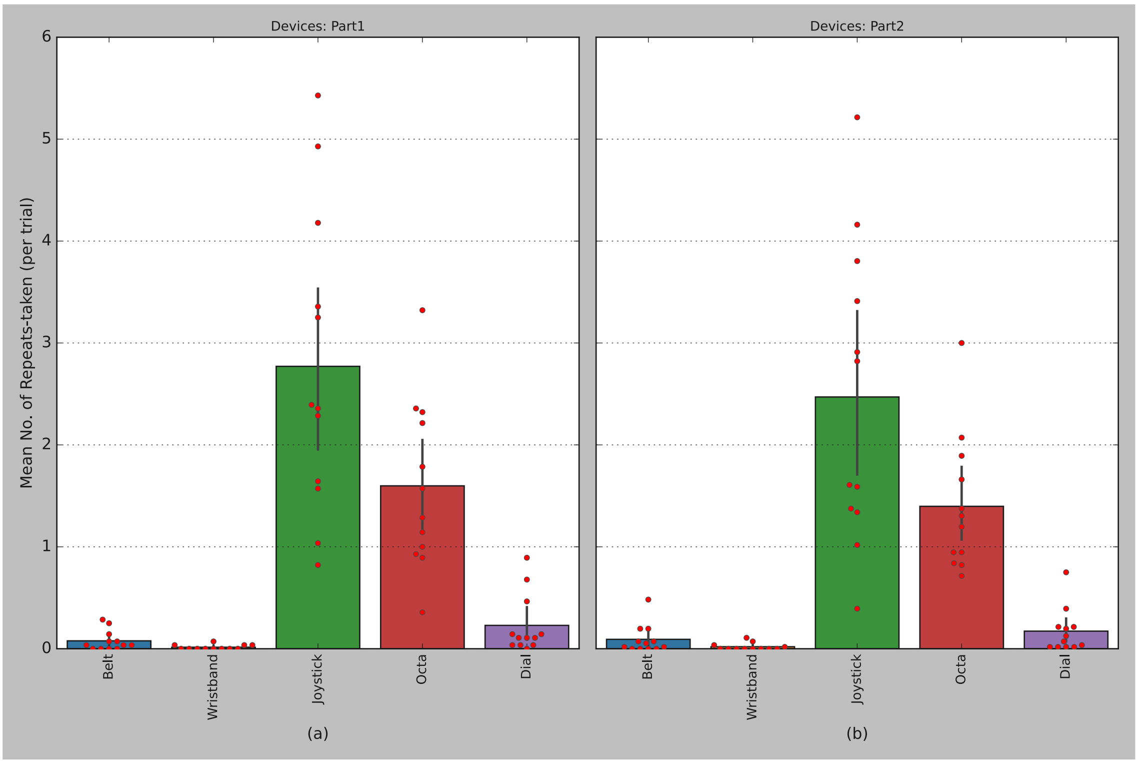

Figure 6.7 Visualisation of the means for the repeats taken per trial during direction-only and direction-and-proximity parts. Error bars represent the 95% confidence interval for the mean.

Table 6.7 Mean results of repeats taken per trial during direction-only and direction-and-proximity parts

Device	Best point estimate: Mean repeats-taken (Part1) (a)	Best point estimate: Mean repeats-taken (Part2) (b)
Belt	0.1	0.1
Wristband	0	0
Joystick	2.8	2.5
JoystickOctagon	1.6	1.4
Dial	0.2	0.2

Figure 6.7(a) and Table 6.7(a) show performance during the direction-only (Part1) scenario. It shows that the round joystick (active proprioceptive device without external tactile markers) took significantly more repeats per trial than other devices during the direction-only scenario. The wristband and belt (passive devices) had a significantly better number of repeats-taken performance than the round and octagonal joystick (active devices). However, the dial as an active proprioceptive device was an exception from the other two active devices.

Figure 6.7(b) and Table 6.7(b) show performance during the direction-and-proximity (Part2) scenario. It shows that both joysticks (active devices) took significantly more repeats per trial than passive devices also during part2. And again, the dial as an active proprioceptive device was an exception from the other two active devices.

Performing an overall ANOVA test for the time-taken variable-of-interest confirmed statistical differences ($F=30.8$, $p<0.001$) among the devices. Therefore, next, each part/scenario will be tested separately.

For part1, the ANOVA test confirmed statistical differences ($F= 29.4$, $p<0.001$) among the devices. Tukey’s HSD test results, summarised in Table 6.8, show significant differences in the repeats taken per trial across devices. In addition, Figure 6.8 shows, if any, significant differences among devices with respect to the belt. The belt and wristband (passive vibrotactile devices) took fewer repeats per trial than the joystick and octagonal joystick (active proprioceptive devices). However, there was no significant difference between the dial and the passive devices. The wristband was the best-performing device, while the round joystick was the lowest.

Table 6.8 Tukey HSD results for mean number of repeats-taken during the direction-only part

Multiple Comparison of Means – Tukey HSD, FWER=0.05						
group1	group2	Mean diff.	p-adj.	lower	upper	Reject H0
Belt	Dial	0.1518	0.9889	-0.7403	1.0438	FALSE
Belt	Joystick	2.6935	<0.001	1.8014	3.5855	TRUE
Belt	JoystickOctagon	1.5208	0.0001	0.6288	2.4129	TRUE
Belt	Wristband	-0.0625	0.9996	-0.9545	0.8295	FALSE
Dial	Joystick	2.5417	<0.001	1.6496	3.4337	TRUE
Dial	JoystickOctagon	1.369	0.0006	0.477	2.2611	TRUE
Dial	Wristband	-0.2143	0.9605	-1.1063	0.6778	FALSE
Joystick	JoystickOctagon	-1.1726	0.0043	-2.0647	-0.2806	TRUE
Joystick	Wristband	-2.756	<0.001	-3.648	-1.8639	TRUE
JoystickOctagon	Wristband	-1.5833	0.0001	-2.4754	-0.6913	TRUE

Notes:
Highlighted rows are the comparisons where the means of the devices are significantly different from each other.
Family Wise Error Rate (FWER).
Null hypothesis (H0): There is no difference in means; Reject H0 value TRUE means rejecting the null hypothesis.

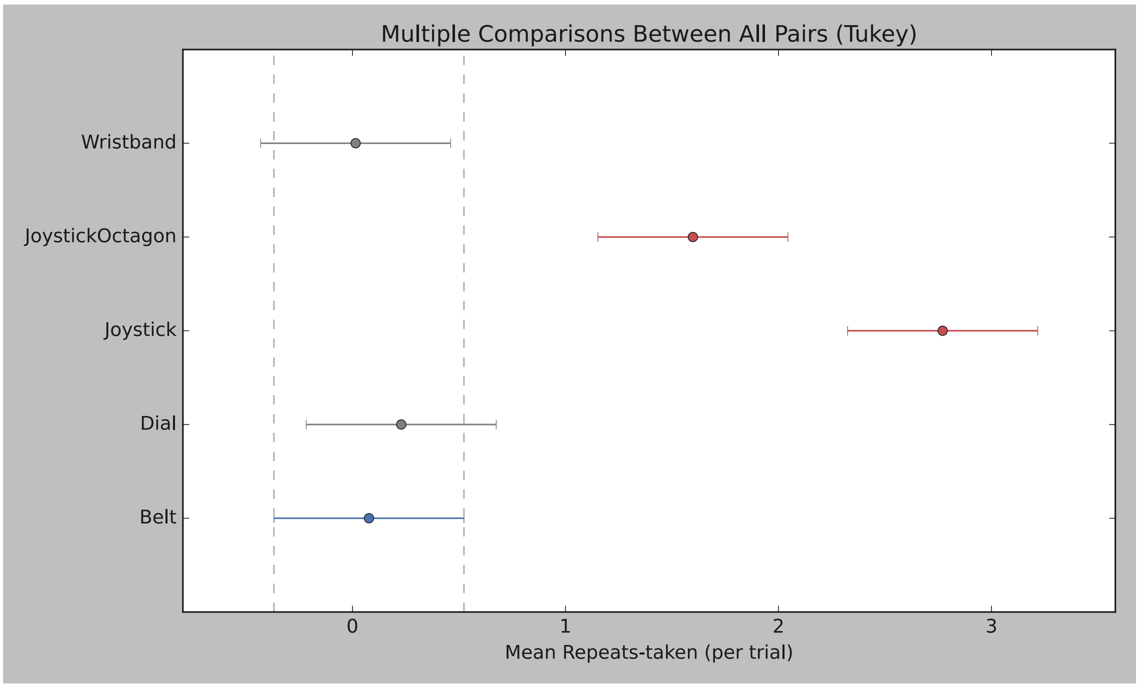

Figure 6.8 Visualisation of Tukey HSD results for mean number of repeats-taken during the Direction-only part with respect to the belt. Error bars represent the 95% confidence interval for the mean.

For part2, the ANOVA test confirmed statistical differences (F= 26, p<0.001) among the devices. Tukey's HSD test results, summarised in Table 6.9, show significant differences in the repeats taken per trial across devices. In addition, Figure 6.9 shows, if any, significant differences among devices with respect to the belt. The belt and wristband (passive vibrotactile devices) took fewer repeats per trial than the joystick and octagonal joystick (active proprioceptive devices). However, there was no significant difference between the dial and the passive devices. The wristband was the best-performing device, while the round joystick was the lowest.

Table 6.9 Tukey HSD results for mean repeats-taken during the direction-and-proximity part

Multiple Comparison of Means – Tukey HSD, FWER=0.05						
group1	group2	Mean diff.	p-adj.	lower	upper	Reject H0
Belt	Dial	0.0804	0.9988	-0.7621	0.9228	FALSE
Belt	Joystick	2.378	<0.001	1.5355	3.2204	TRUE
Belt	JoystickOctagon	1.3051	0.0005	0.4626	2.1475	TRUE
Belt	Wristband	-0.0729	0.9992	-0.9154	0.7695	FALSE
Dial	Joystick	2.2976	<0.001	1.4552	3.1401	TRUE
Dial	JoystickOctagon	1.2247	0.0013	0.3823	2.0671	TRUE

Dial	Wristband	-0.1533	0.9857	-0.9957	0.6892	FALSE
Joystick	JoystickOctagon	-1.0729	0.0061	-1.9154	-0.2305	TRUE
Joystick	Wristband	-2.4509	<0.001	-3.2933	-1.6085	TRUE
JoystickOctagon	Wristband	-1.378	0.0002	-2.2204	-0.5355	TRUE

Notes:
Highlighted rows are the comparisons where the means of the devices are significantly different from each other.
Family Wise Error Rate (FWER).
Null hypothesis (H0): There is no difference in means; Reject H0 value TRUE means rejecting the null hypothesis.

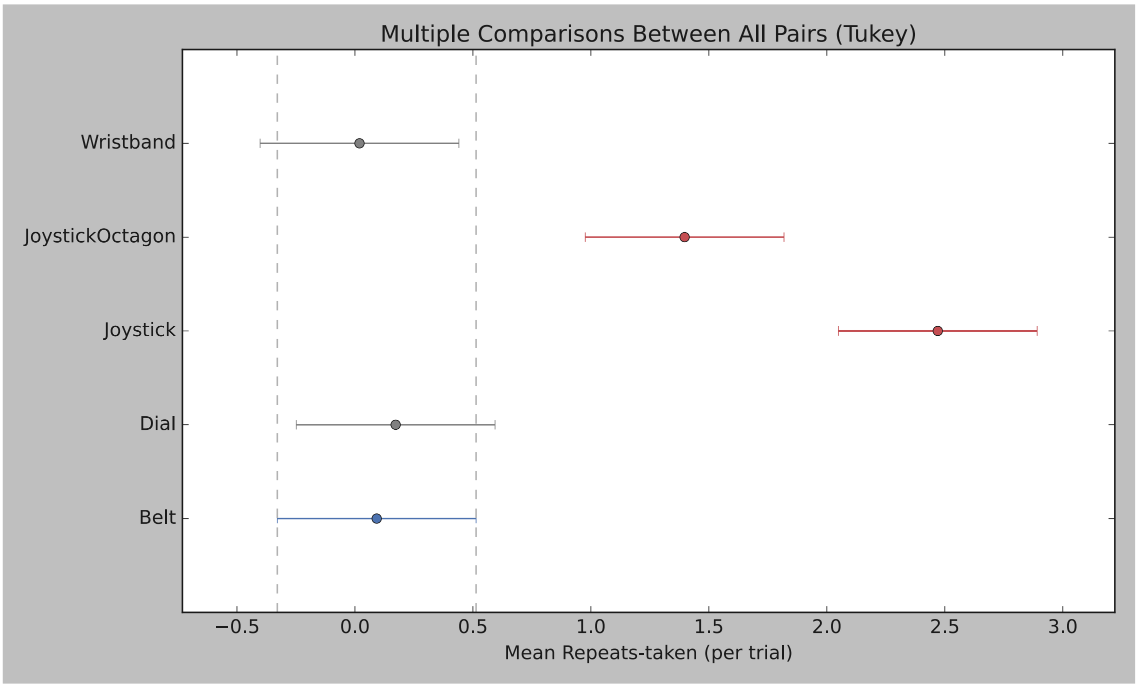

Figure 6.9 Visualisation of Tukey HSD results for mean repeats-taken during the Direction-and-proximity part with respect to the belt. Error bars represent the 95% confidence interval for the mean.

To conclude this section, the results show that the active proprioceptive-vibrotactile devices require more or the same (in the case of the dial) number of repeats per trial than the passive vibrotactile devices for both scenarios (direction-only and direction-and-proximity).

The following section presents the effectiveness of each device in terms of experienced workload during the test.

6.4 Overall Workload (OW)

This section compares the mean overall workload across all the devices.

Firstly, the section presents, for each device, the mean overall workload during the direction-only scenario (part1) and direction-and-proximity scenario (part2). After that, the section presents the results of a one-way ANOVA test for the overall workload experienced. And finally, the section presents the results of a Tukey's HSD test for the overall workload.

Figure 6.10 consists of two subplots; subplot-a shows the mean overall workload experienced during the direction-only part of the test and subplot-b shows the mean overall workload during the direction-and-proximity part of the test.

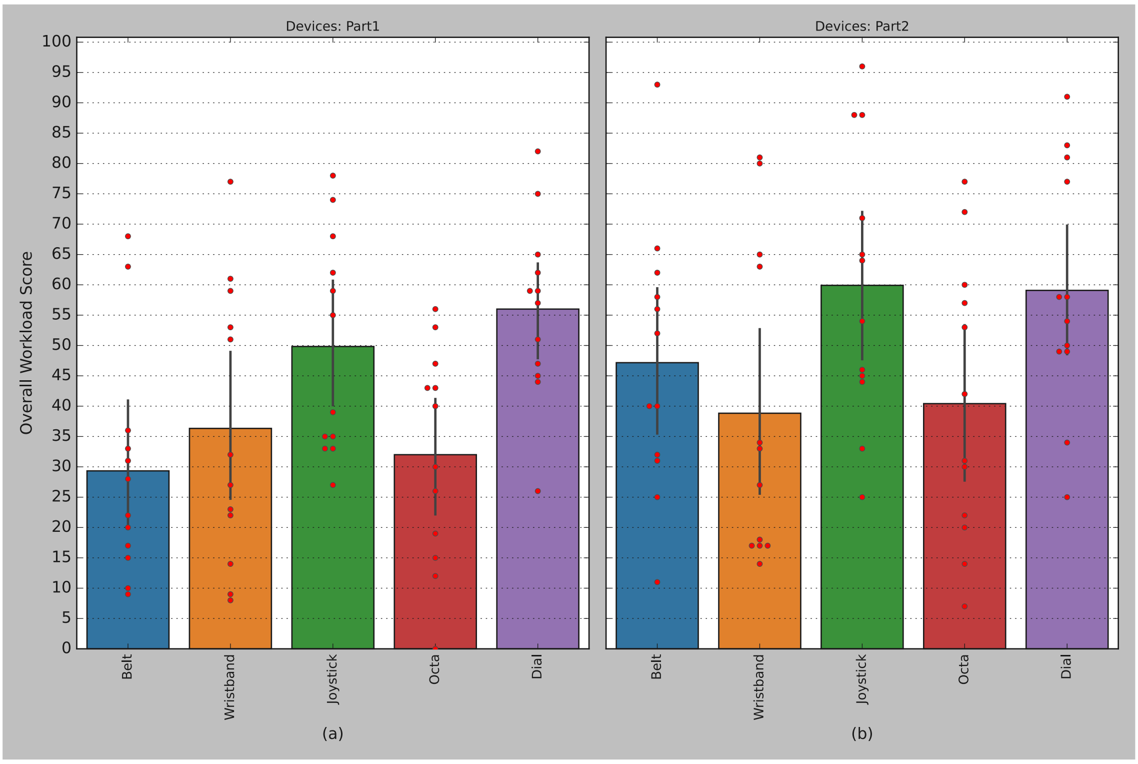

Figure 6.10 Visualisation of the means for the overall workload during direction-only and direction-and-proximity parts. Error bars represent the 95% confidence interval for the mean.

Table 6.10 Mean results of the overall workload during direction-only and direction-and-proximity parts

Device	Best point estimate: Mean overall workload (Part1) (a)	Best point estimate: Mean overall workload (Part2) (b)
Belt	29.3	47.2
Wristband	36.3	38.8

Joystick	49.8	59.9
JoystickOctagon	32	40.4
Dial	56	59.1

Figure 6.10(a) and Table 6.10(a) show performance during the direction-only (Part1) scenario. It shows that the round joystick and dial (active proprioceptive devices) imparted a higher experienced overall workload than the wristband and belt (passive devices) during the direction-only scenario. However, the octagonal joystick's performance as an active proprioceptive device was an exception to the other two active devices.

Figure 6.10(b) and Table 6.10(b) show performance during the direction-and-proximity (Part2) scenario. It shows, like part1, that the active devices imparted a higher workload on the users than the passive devices during the direction-&-proximity scenario (part2). However, the octagonal joystick's performance as an active proprioceptive device was an exception to the other two active devices.

Performing an overall ANOVA test for the time-taken variable-of-interest confirmed statistical differences ($F=5.8$, $p<0.001$) among the devices. Therefore, next, each part/scenario will be tested separately.

For part1, the ANOVA test confirmed statistical differences ($F= 4.6$, $p = 0.003$) among the devices. Tukey's HSD test results, summarised in Table 6.11, show significant differences in the mean overall workload across devices. In addition, Figure 6.11 shows any significant difference among devices with respect to the belt. The belt and wristband (passive vibrotactile devices) imparted a lower overall workload than the round-rimmed joystick and dial (active proprioceptive devices). However, there was no significant difference between the octagonal joystick and the passive devices.

Table 6.11 Tukey HSD results for mean overall workload during the direction-only part

Multiple Comparison of Means – Tukey HSD, FWER=0.05						
group1	group2	Mean diff.	p-adj.	lower	upper	Reject H0
Belt	Dial	26.6667	0.0083	5.0931	48.2403	TRUE
Belt	Joystick	20.5	0.0701	-1.0736	42.0736	FALSE
Belt	JoystickOctagon	2.6667	0.9967	-18.9069	24.2403	FALSE
Belt	Wristband	7	0.8899	-14.5736	28.5736	FALSE
Dial	Joystick	-6.1667	0.9276	-27.7403	15.4069	FALSE
Dial	JoystickOctagon	-24	0.022	-45.5736	-2.4264	TRUE

Dial	Wristband	-19.6667	0.09	-41.2403	1.9069	FALSE
Joystick	JoystickOctagon	-17.8333	0.1506	-39.4069	3.7403	FALSE
Joystick	Wristband	-13.5	0.4041	-35.0736	8.0736	FALSE
JoystickOctagon	Wristband	4.3333	0.9794	-17.2403	25.9069	FALSE
Notes: Highlighted rows are the comparisons where the means of the devices are significantly different from each other. Family Wise Error Rate (FWER). Null hypothesis (H0): There is no difference in means; Reject H0 value TRUE means rejecting the null hypothesis.						

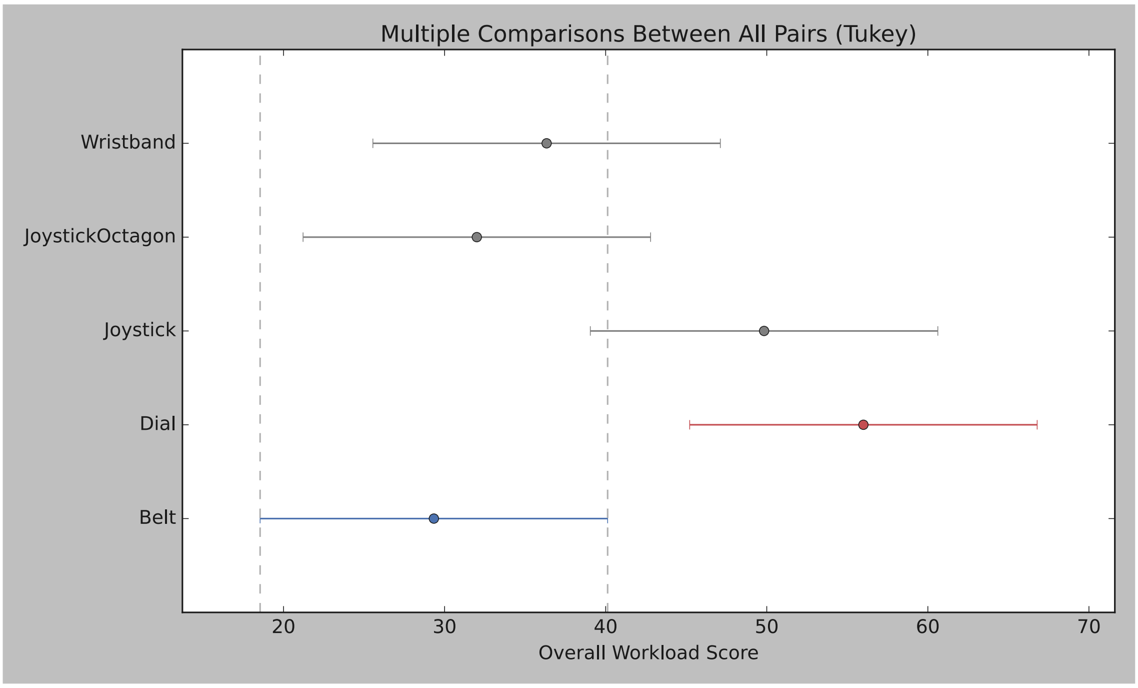

Figure 6.11 Visualisation of Tukey HSD results for mean overall workload during the direction-only part with respect to the belt. Error bars represent the 95% confidence interval for the mean.

For part2, the ANOVA test confirmed a lack of statistical differences (F= 2.3, p = 0.07) among the devices. Tukey's HSD test results, summarised in Table 6.12, show in detail the lack of significant differences in the mean overall workload across devices. In addition, Figure 6.12 shows any significant difference among devices with respect to the belt. However, there was no significant difference between the devices.

Table 6.12 Tukey HSD results for mean overall workload during the direction-and-proximity part

Multiple Comparison of Means – Tukey HSD, FWER=0.05

group1	group2	Mean diff.	p-adj.	lower	upper	Reject H0
Belt	Dial	11.9167	0.7073	-14.44	38.2733	FALSE
Belt	Joystick	12.75	0.6526	-13.6066	39.1066	FALSE
Belt	JoystickOctagon	-6.75	0.9505	-33.1066	19.6066	FALSE
Belt	Wristband	-8.3333	0.8988	-34.69	18.0233	FALSE
Dial	Joystick	0.8333	1	-25.5233	27.19	FALSE
Dial	JoystickOctagon	-18.6667	0.2809	-45.0233	7.69	FALSE
Dial	Wristband	-20.25	0.2077	-46.6066	6.1066	FALSE
Joystick	JoystickOctagon	-19.5	0.2405	-45.8566	6.8566	FALSE
Joystick	Wristband	-21.0833	0.175	-47.44	5.2733	FALSE
JoystickOctagon	Wristband	-1.5833	0.9998	-27.94	24.7733	FALSE

Notes:
Highlighted rows are the comparisons where the means of the devices are significantly different from each other.
Family Wise Error Rate (FWER).
Null hypothesis (H0): There is no difference in means; Reject H0 value TRUE means rejecting the null hypothesis.

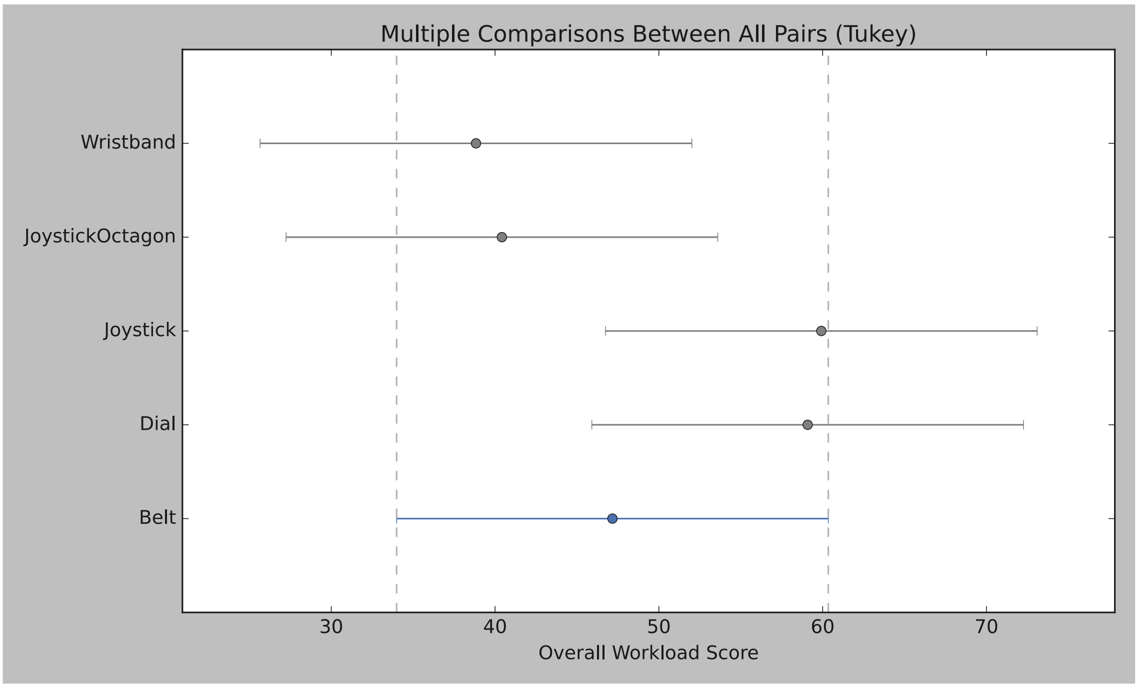

Figure 6.12 Visualisation of Tukey HSD results for mean overall workload during the direction-and-proximity part with respect to the belt. Error bars represent the 95% confidence interval for the mean.

To conclude this section, the results show that, during the direction-only scenario, the active proprioceptive-vibrotactile devices impart a higher or same (in the case of the octagonal joystick) overall workload on the users than the passive vibrotactile devices, whereas during the direction-and-proximity scenario, no significant difference was detected among the devices.

The following section presents the effectiveness of each device in terms of the system's usability during the test.

6.5 System Usability Score (SUS)

This section compares the mean system usability score across all the devices.

Firstly, the section presents, for each device, the mean System Usability Score (SUS) during the direction-only scenario (part1) and direction-and-proximity scenario (part2). After that, the section presents the results of a one-way ANOVA test for the SUS. And finally, the section presents the results of a Tukey's HSD test for the SUS.

Figure 6.13 consists of two subplots; subplot-a shows mean SUS during the direction-only part of the test and subplot-b shows mean SUS during the direction-and-proximity part of the test.

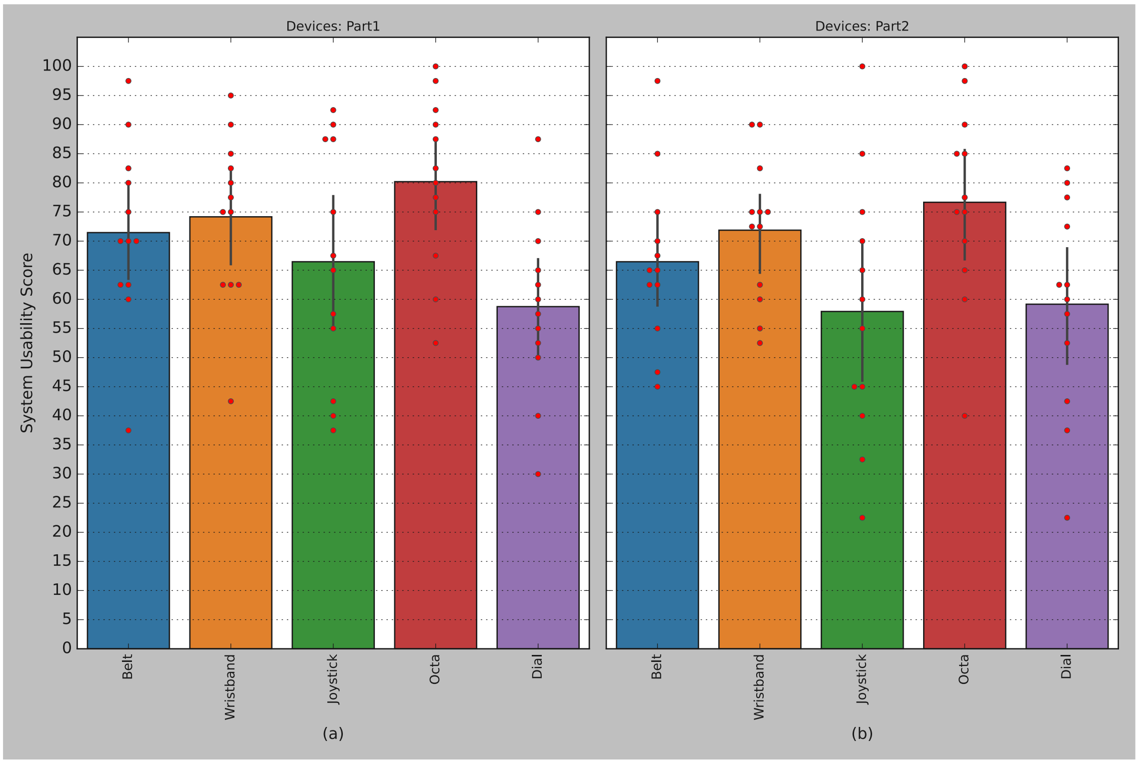

Figure 6.13 Visualisation of the means for the system usability score during direction-only and direction-and-proximity parts. Error bars represent the 95% confidence interval for the mean.

Table 6.13 Mean results of the system usability score during direction-only and direction-and-proximity parts

Device	Best point estimate: Mean SUS (Part1) (a)	Best point estimate: Mean SUS (Part2) (b)
Belt	71.5	66.5
Wristband	74.2	71.9
Joystick	66.5	57.9
JoystickOctagon	80.2	76.7
Dial	58.8	59.2

Figure 6.13(a) and Table 6.13(a) show performance during the direction-only (Part1) scenario. It shows that the round-rimmed joystick and dial (active proprioceptive devices) had a lower usability score than the passive devices during the direction-only scenario. However, the octagonal joystick as an active proprioceptive device was an exception from the other two active devices. The same pattern was present during the direction-and-proximity scenario (part2), as shown in Figure 6.13(b) and Table 6.13(b).

Performing an overall ANOVA test for the time-taken variable-of-interest confirmed statistical differences ($F=5.5$, $p<0.001$) among the devices. Therefore, next, each part/scenario will be tested separately.

For part1, the ANOVA test confirmed statistical differences ($F= 2.99$, $p = 0.026$) among the devices. Tukey's HSD test results, summarised in Table 6.14, show significant differences in the mean usability scores across devices. In addition, Figure 6.14 shows, if any, significant differences among devices with respect to the belt. The octagonal joystick (active proprioceptive device) has a higher usability score than the other active proprioceptive and passive vibrotactile devices. However, there was no significant difference between the devices except in one case: the octagonal joystick was significantly better than the dial.

Table 6.14 Tukey HSD results for mean system usability score during the direction-only part

Multiple Comparison of Means – Tukey HSD, FWER=0.05						
group1	group2	Mean diff.	p-adj.	lower	upper	Reject H0
Belt	Dial	-12.7083	0.3199	-31.3889	5.9723	FALSE
Belt	Joystick	-5	0.9422	-23.6806	13.6806	FALSE
Belt	JoystickOctagon	8.75	0.6794	-9.9306	27.4306	FALSE

Belt	Wristband	2.7083	0.994	-15.9723	21.3889	FALSE
Dial	Joystick	7.7083	0.7717	-10.9723	26.3889	FALSE
Dial	JoystickOctagon	21.4583	0.0167	2.7777	40.1389	TRUE
Dial	Wristband	15.4167	0.1518	-3.2639	34.0973	FALSE
Joystick	JoystickOctagon	13.75	0.2451	-4.9306	32.4306	FALSE
Joystick	Wristband	7.7083	0.7717	-10.9723	26.3889	FALSE
JoystickOctagon	Wristband	-6.0417	0.891	-24.7223	12.6389	FALSE
Notes: Highlighted rows are the comparisons where the means of the devices are significantly different from each other. Family Wise Error Rate (FWER). Null hypothesis (H0): There is no difference in means; Reject value H0 TRUE means rejecting the null hypothesis.						

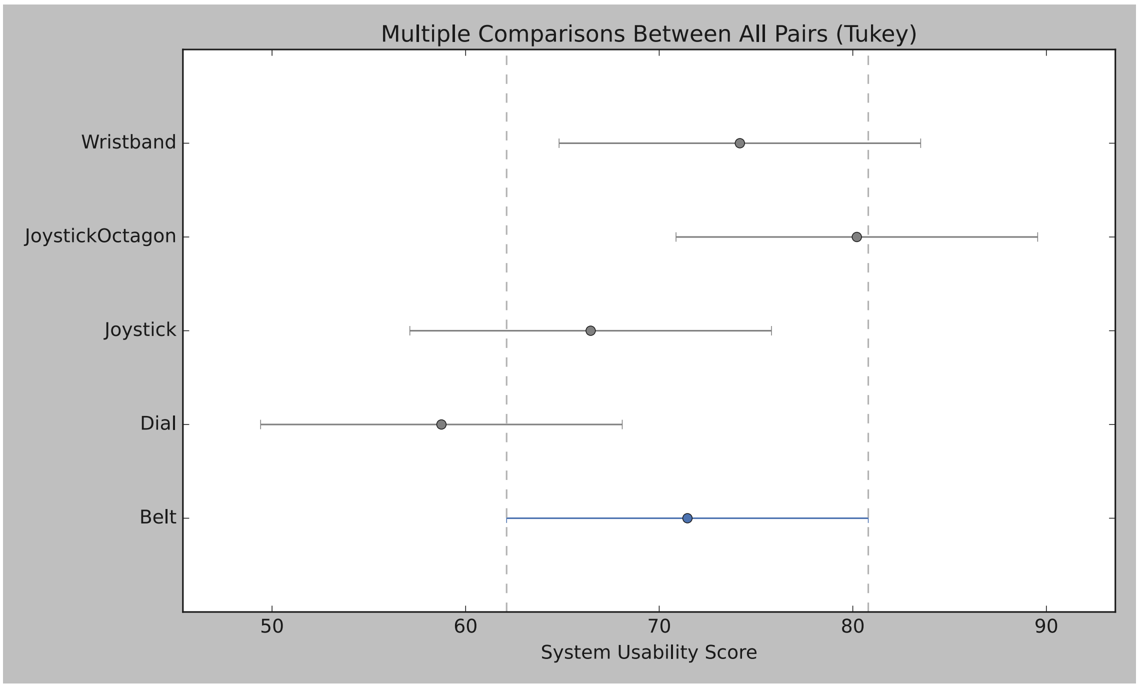

Figure 6.14 Visualisation of Tukey HSD results for the mean system usability scores during the direction-only part with respect to the belt. Error bars represent the 95% confidence interval for the mean.

For part2, the ANOVA test confirmed statistical differences (F= 2.6, p = 0.045) among the devices. Tukey's HSD test results, summarised in Table 6.15, show significant differences in the mean usability scores across devices. In addition, Figure 6.15 shows, if any, significant differences among devices with respect to the belt. However, there was no significant difference between the devices.

Table 6.15 Tukey HSD results for mean system usability score during the direction-and-proximity part

Multiple Comparison of Means – Tukey HSD, FWER=0.05						
group1	group2	Mean diff.	p-adj.	lower	upper	Reject H0
Belt	Dial	-7.2917	0.8382	-27.1669	12.5836	FALSE
Belt	Joystick	-8.5417	0.7444	-28.4169	11.3336	FALSE
Belt	JoystickOctagon	10.2083	0.5996	-9.6669	30.0836	FALSE
Belt	Wristband	5.4167	0.9385	-14.4586	25.2919	FALSE
Dial	Joystick	-1.25	0.9998	-21.1253	18.6253	FALSE
Dial	JoystickOctagon	17.5	0.1094	-2.3753	37.3753	FALSE
Dial	Wristband	12.7083	0.3821	-7.1669	32.5836	FALSE
Joystick	JoystickOctagon	18.75	0.0733	-1.1253	38.6253	FALSE
Joystick	Wristband	13.9583	0.2889	-5.9169	33.8336	FALSE
JoystickOctagon	Wristband	-4.7917	0.96	-24.6669	15.0836	FALSE
Notes: Highlighted rows are the comparisons where the means of the devices are significantly different from each other. Family Wise Error Rate (FWER). Null hypothesis(H0): There is no difference in means; Reject H0 value TRUE means rejecting the null hypothesis.						

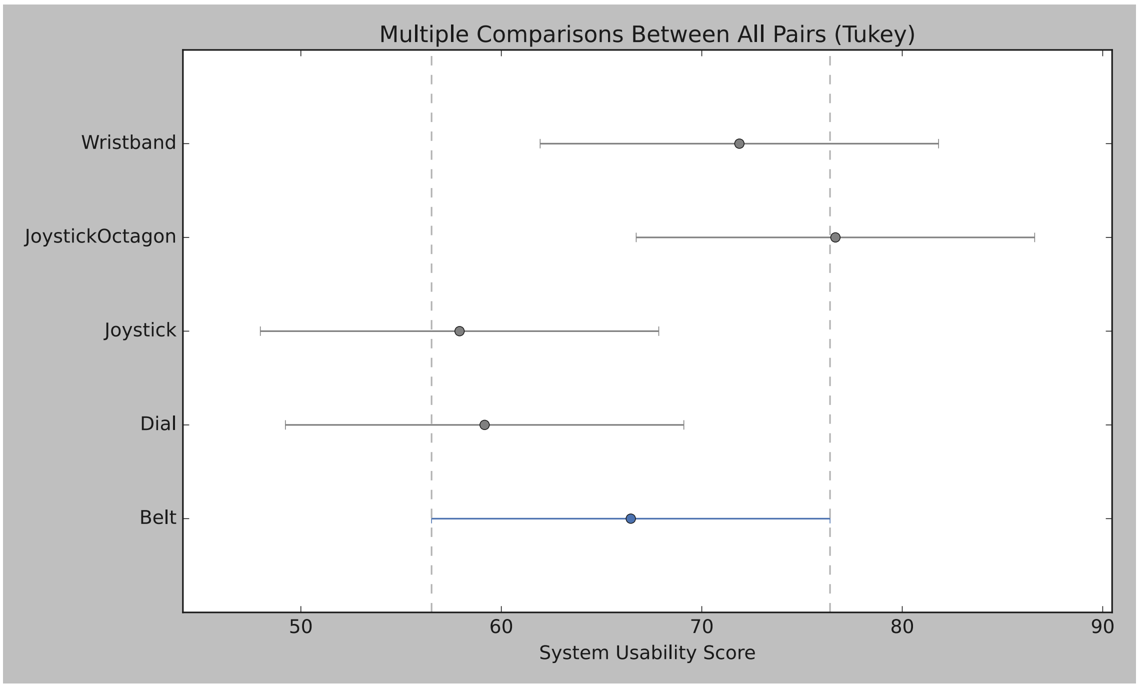

Figure 6.15 Visualisation of Tukey HSD results for the mean system usability scores during the direction-and-proximity part with respect to the belt. Error bars represent the 95% confidence interval for the mean.

To conclude this section, the results show that, during the direction-only scenario, the active proprioceptive-vibrotactile devices have the same perceived usability as the passive vibrotactile devices. Whereas during the direction-and-proximity scenario, no significant difference was detected among the devices.

6.6 Findings based on the interviews

This section presents the qualitative ranking of the tested displays. Each of the five devices was evaluated by 12 participants. During the informal interviews at the end of each session, participants were asked to rank the devices they had tested so far in order of preference. Table 6.16 summarises the final order of preference provided by the participants at the end of their last sessions. In addition, Table 6.17 summarises the final preference for the mode of interaction.

Table 6.16 Ordering of devices based on the participants' preference

Device \ Ranking	1st	2nd	3rd	4th	5th	Total
Belt	3 (25%)	4 (33%)	3 (25%)	1 (8%)	1 (8%)	12
Wristband	5 (42%)	5 (42%)	0	2 (17%)	0	12
Joystick (Round)	0	0	1 (8%)	5 (42%)	6 (50%)	12
Joystick (Octagonal)	2 (17%)	1 (8%)	6 (50%)	3 (25%)	0	12
Dial	2 (17%)	2 (17%)	2 (17%)	1 (8%)	5 (42%)	12
Total	12	12	12	12	12	60

Table 6.17 Participants' preference for mode of interaction

Mode \ Preference	1st
Passive	8 (67%)
Active	4 (33%)
Total	12

The following section concludes this chapter of comparisons with a summary of key highlights.

6.7 Conclusion

This chapter has looked at each variable of interest across the passive vibrotactile and active proprioceptive-vibrotactile devices. Passive vibrotactile devices were the wristband and belt, whereas the active proprioceptive-vibrotactile devices were the round joystick, octagonal joystick, and dial. Performance was measured for two scenarios: direction-only and direction-and-proximity. Using the belt as a reference point for comparisons, Figure 6.16 and Figure 6.17 summarise the statistical findings presented earlier in the chapter.

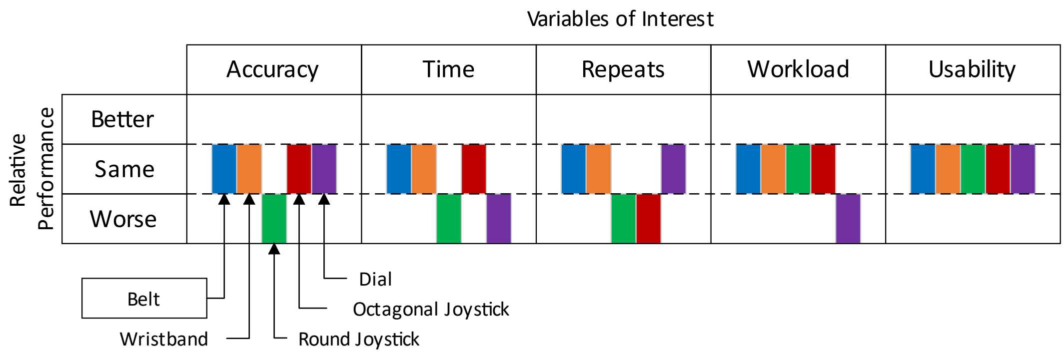

Figure 6.16 Summary of statistical comparisons to the belt for the direction-only part

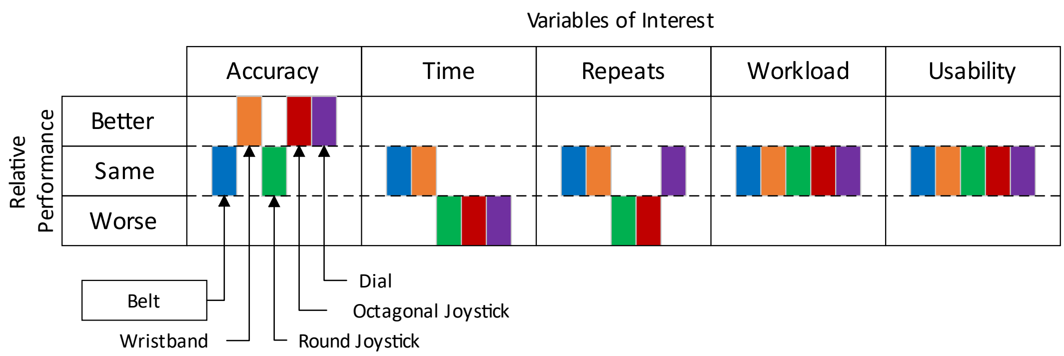

Figure 6.17 Summary of statistical comparisons to the belt for the direction-and-proximity part

During the direction-only scenario:

- No difference in performance was detected between the belt and the wristband for any of the five variables of interest
- The round joystick's performance was lower than the belt's for the objective measures (accuracy, time-taken, repeats-taken). However, for subjective measures (experienced workload and perceived usability), there was no statistical difference in performance
- The number of repeats required were significantly more for the joysticks (round and octagonal) than for the passive devices

- The experienced workload was significantly more for the dial in comparison to the belt
- No difference in usability was detected in comparison to the belt

During the direction-and-proximity scenario:

- The wristband was more accurate than the belt while no difference was detected between them for other variables of interest
- The active devices' (round joystick, octagonal joystick, and dial) time performance was worse than the belt
- The number of repeats required were significantly more for the joysticks (round and octagonal) than for the belt
- No difference in the experienced workload was detected in comparison to the belt
- No difference in usability was detected in comparison to the belt

In short, based on the quantitative analysis, both passive devices (belt and wristband) would be the optimal choice for the direction-only scenarios, while the wristband would be the optimal choice for the direction-and-proximity scenarios.

However, based on the qualitative input from the participants, it was found that out of the 12 participants, 4 (33%) expressed a preference for using one of the active devices. Specifically, 2 participants preferred the octagonal-rimmed joystick, while the other 2 participants preferred the dial. These preferences emerged after testing all five different haptic prototypes.

The next chapter will critically discuss these findings, conclude the thesis, and lay out the next steps for future research.

Chapter 7
Discussion, Conclusions, and Future-Research

This final chapter provides a comprehensive synthesis and analysis of the research findings, draws clear conclusions, and suggests avenues for future research. It reinstates and discusses the research results in the light of research questions (main and sub); it compares and points out interesting findings for different aspects of performance across the five prototypes and the two scenarios (direction-only and direction-and-proximity); where applicable, it points out relevant published research findings that support or contradict the findings of this research. Then the chapter makes clear conclusive statements about the research findings, contributions, and limitations. Finally, the chapter ends with a section that lays out the next steps that future research can take in order to build on the findings at hand, mitigate the limitations, and further the understanding of haptic displays for navigation and in general.

This chapter is divided into four sections: Summary, discussion, conclusions, and future research: the discussion section critically discusses the research findings; the conclusion section covers conclusive statements, contributions, and limitations of the research project; and finally, the future-research section layouts next steps for future research projects based on the findings, contributions, and limitations of this research project.

7.1 Summary

This research aims to evaluate and compare the performance of two methods of haptically communicating navigational information: the passive vibrotactile method and the active proprioceptive-vibrotactile method. The passive vibrotactile method is widely used in the field of haptics for navigation by researchers and industry. And the active proprioceptive-vibrotactile method is widely used to interact with machines where spatial control is required. The research evaluates the two methods independently and then compares them. The evaluation followed by comparison allows a richer understanding of the advantages and disadvantages and differences and similarities of both methods for communicating navigational information. See Chapter2 for detailed background information and Chapter3 for a detailed explanation of the methodology.

As explained in detail in Chapter2, and recapped in Figure 7.1, the main and sub-research questions behind the aim of this research are:

- Main research question: How intuitive and effective is an active proprioceptive vibrotactile device compared to a passive vibrotactile device for navigation?
- Sub-research-question-1: How intuitive and effective is a passive single-element vibrotactile device for navigation?
- Sub-research-question-2: How intuitive and effective is an active proprioceptive vibrotactile device for navigation?

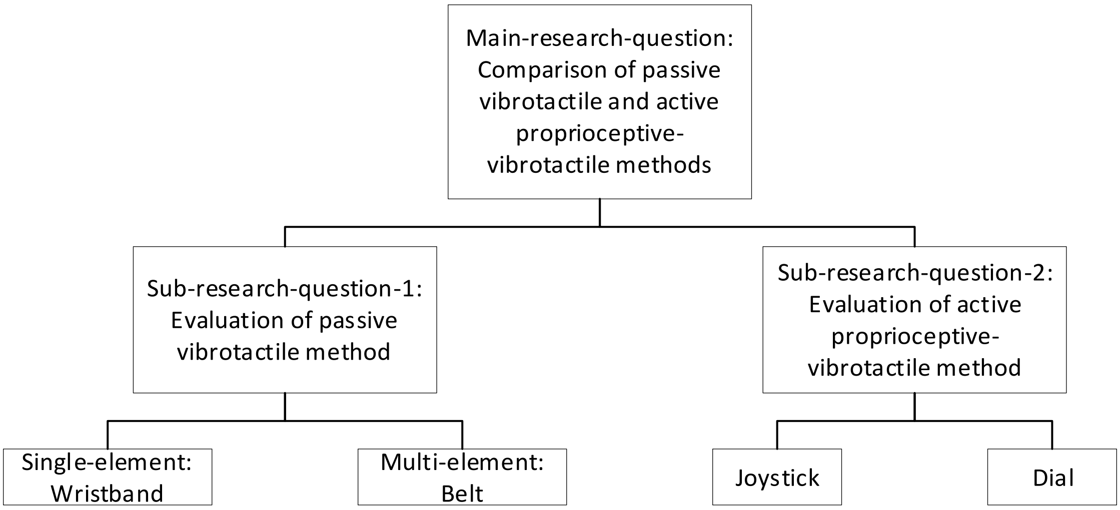

Figure 7.1: High-level research link between the main and sub-research questions and the haptic methods

Accuracy, time, repetition, experienced workload, and perceived usability are the five aspects which were evaluated for each haptic prototype. In the following sub-sections, for each prototype, results from chapters 4, 5, and 6 are revisited to complement and or contrast with published knowledge.

7.1.1 Haptic Belt

This research tested the multi-element passive vibrotactile method using a haptic belt. The reason behind choosing a haptic belt is its popularity and reputation for good performance (see Chapter2, section2.5). This research evaluates the haptic belt using an elaborate methodology explained earlier (see Chapter3). The results of the belt formed a benchmark to compare the performance of other prototypes - performance observed during this research and, where possible, in the published literature was used. In this subsection, each variable of interest is discussed in turn.

Accuracy

During this research, using a belt with 7 vibration motors, an accuracy of 96% (95%CI: 94, 98) was observed for direction-only stimuli and a lower accuracy of 83% (95%CI: 77, 90) was observed for direction-and-proximity stimuli.

Whereas in the published literature, though not direct replications, studies show comparable results. For example, Cholewiak et al. (2004) used belts with 6, 8, and 12 vibration motors and observed 97%, 92%, and 74% average accuracies, respectively.

This research shows that adding more information to the stimulus, is possible, and comes at the expense of accuracy, that is, it reduces the accuracy of the haptic belt.

Time-taken

During this research, the mean time-taken to respond for stimuli which indicated direction-only was 4 (95%CI: 3.3, 4.8) seconds and direction-and-proximity was 4.9 (95%CI: 4, 5.8) seconds.

This amount of time taken observed in this research is more than the other published results, for example, Cholewiak et al.'s (2004) results show approximately an average of 1 second and Hancock et al.'s (2013) show 2 seconds. The lower time performance of the belt during this research could be a result of participants being blindfolded and allowed to repeat the stimulus during a given trial, and this research is not a replica of the example studies.

Repeats-taken

During this research, the mean repeats-taken to respond for stimuli which indicated direction-only were 0.08 (95%CI: 0.01, 0.14) repeats per trial and direction-and-proximity were 0.09 (95%CI: 0, 0.18) repeats per trial. These numbers show that stimuli were recognised on the first exposure: 8 repeats per 100 trials for direction-only and 9 repeats per 100 trials for direction-and-proximity stimuli.

This variable of interest hasn't been measured in the published literature.

Experienced mental workload

During this research, the mean experienced mental workload score, assessed using NASA's Task Load Index (TLX) for stimuli which indicated direction-only was 29 (95% CI: 17, 41) and direction-and-proximity was 47 (95% CI: 33, 61). Though the studies are not a replica, the observed results in this research are comparable to that of Hancock et al.'s (2013) who also used a belt: 24.6 TLX score.

The effectiveness of the belt, in terms of the experienced mental workload, was affected by the addition of proximity information to the stimuli.

System Usability Score

During this research, the mean perceived usability score of a belt, assessed using Digital Equipment Co.'s System Usability Scale (SUS) for stimuli which indicated direction-only was 71 (95% CI: 62, 81) and direction-and-proximity was 66 (95% CI: 57, 76).

Though the average perceived usability of the belt decreased with the encoding of proximity to the stimuli, the difference is statistically not significant.

Bangor (2009) found in his research that a score of 70 or above indicates good usability for the interface, a score below that indicates marginally acceptable usability, and a score below 50 indicates unacceptable usability for the given interface. Based on this classification, the belt's perceived usability as an interface for navigation was good.

For example, Hsieh et al.'s (2019) research used a haptic glove to guide the user's hand to the point of interest; it scored 71.9 as an interface for orientation.

7.1.2 Haptic Wristband

This research tested the single-element passive vibrotactile method using a haptic wristband. The reason behind choosing a haptic wristband is its simplicity and prevalence in the form of a smartwatch (see Chapter 2, section 2.5). This research evaluates the haptic wristband using an elaborate methodology explained earlier (see Chapter 3). The results of the wristband formed another benchmark to compare the performance of other prototypes - performance observed during this research and, where possible, in the published literature was used. In this subsection, each variable of interest is discussed in turn.

Accuracy

During this research, using a wristband with 1 vibration motor, an accuracy of 97.6% (95%CI: 95.4, 99.9) was observed for direction-only stimuli and a higher accuracy of 98.4% (95%CI: 97, 99.8) was observed for direction-and-proximity stimuli.

Knowledge-gap-1 identified (see Chapter 2, section 2.5) is a lack of investigation of single-element passive vibrotactile devices for navigation. This lack is rooted in an untested notion that single-element devices would be limited, and therefore, multi-element would be better for communicating navigational or spatial information (Kaczmarek et al., 1991; Tsukada and Yasumura, 2004; Wilkinson et al., 2019). However, in terms of accuracy, results observed during this research (point estimates: 97.6% and 98.4%) provide evidence against the aforementioned notion.

This research shows that adding more information (proximity) to the stimulus, in the wristband's case, is possible, and does not come at the expense of accuracy whereas in the belt's case accuracy was affected. Compared to the multi-element prototype (belt), the single-element prototype (wristband) is statistically as accurate for direction-only stimuli and more accurate for direction-and-proximity stimuli.

Haptic wristbands are gaining popularity and are already commercially available, for example, smartwatches (Apple, 2023), fitness bands, and assistive bands (Sunu Band, 2023). However, they haven't been thoroughly investigated by researchers as a haptic display for navigation. Ogrinc et al. (2018) experimented with using two bands, which were worn on each upper arm, to help the deaf-blind with horseback riding; they found using two bands effective for communicating simple directions such as left and right.

Time-taken

During this research, the mean time taken to respond for stimuli which indicated direction-only was 6.1 (95%CI: 5.3, 6.9) seconds and direction-and-proximity was 5.7 (95%CI: 5.3, 6.0) seconds.

The effectiveness of the wristband in terms of response time was not affected by the addition of proximity information to the stimuli, whereas in the belt's case, encoding of proximity information came at the expense of increased response time and decreased accuracy.

For the direction-only scenario, the belt's performance (point estimate: 4 seconds) was better than the wristband's (point estimate: 6.1 seconds), but this advantage was lost during the direction-and-proximity scenario. The wristband's performance (point estimate: 5.7 seconds) in terms of time taken per trial was approximately equal to that of belts (point estimate: 4.9 seconds) when it came to more rich stimuli (direction and distance).

Repeats-taken

During this research, the mean repeats-taken to respond for stimuli which indicated direction-only was 0.01 (95%CI: 0.01, 0.14) repeats per trial and direction-and-proximity was 0.02 (95%CI: 0, 0.18) repeats per trial. These numbers show that stimuli were recognised on the first exposure: 1 repeat per 100 trials for direction-only and 2 repeats per 100 trials for direction-and-proximity stimuli.

Again, the effectiveness of the wristband in terms of repeats taken was not affected by the addition of proximity information to the stimuli, similar to the belt.

In comparison to the belt (point estimate: 0.08 repeats per trial), the wristband's performance in terms of the repeats taken was better for direction-only stimuli (point estimate: 0.01 repeat per trial), whereas there was no statistical difference in performance for the direction-and-proximity stimuli.

This variable of interest hasn't been measured in the published literature.

Experienced mental workload

During this research, the mean experienced mental workload score, assessed using NASA's Task Load Index (TLX) for stimuli which indicated direction-only was 36 (95% CI: 22, 51) and direction-and-proximity was 39 (95% CI: 22, 55).

The effectiveness of the wristband, in terms of experienced workload, was not affected by the addition of proximity information to the stimuli, unlike the belt.

In comparison to the belt, the wristband's performance in terms of the experienced mental workload was statistically the same for direction-only stimuli (point estimate: Belt 29 TLX vs. Wristband 36 TLX) and for the direction-and-proximity stimuli (point estimate: Belt 47 TLX vs. Wristband 39 TLX). The sample size was small (n=12), and therefore, the power of the research to detect a significant difference was small for the given variable for both scenarios (direction-only and direction-and-proximity: 12% and 13%, respectively). The power could be increased in future studies by increasing the sample size. However, the effect size for both scenarios was small and not greatly different (Cohen's d = 0.33 and 0.35). To increase the power above 80%, the sample size would have to be increased to approximately 300 participants. The cost of increasing the sample size would be high just to confirm an effect size that is not practically large.

System Usability Score

During this research, the mean perceived usability score of a wristband, assessed using Digital Equipment Co.'s System Usability Scale (SUS) for stimuli which indicated direction-only was 74 (95% CI: 65, 83) and direction-and-proximity was 72 (95% CI: 64, 80).

The average perceived usability of the wristband didn't change with the encoding of proximity to the stimuli, the difference is statistically not significant.

Bangor (2009) found in his research that a score of 70 or above indicates good usability for the interface, a score below that indicates marginally acceptable usability, and a score below 50 indicates unacceptable usability for the given interface. Based on this classification, the wristband's perceived usability as an interface for navigation was good.

Hsieh et al.'s (2019) research, as an example, used a multi-element haptic glove to guide the user's hand to the point of interest; it scored 71.9 as an interface for orientation.

7.1.3 Haptic Joystick (Round rim)

Knowledge-gap-2 identified (see Chapter 2, section 2.5) was a lack of investigation of active proprioception in a navigation context. Joysticks are a popular component of human-machine interfaces. Joysticks are effective and intuitive as input devices to machines. Can the reverse be true? That is, can a joystick, an active proprioceptive device, be used as an output device to seek/receive navigational information?

This research tested the single-element active proprioceptive vibrotactile method using three designs. Two of them are variations of a joystick and the third design is dial based. The reason behind choosing a joystick is to address the lack of investigation of their performance as a display in a navigational context (see Chapter 2, section 2.5). This research evaluated each joystick using an elaborate methodology explained earlier (see Chapter 3). The performance of each joystick is compared to the benchmarks established earlier (performance of the belt and the wristband) and other active designs, and, where possible, to the published results of similar devices. In this subsection, each variable of interest is discussed in turn for the round-rimmed joystick.

Accuracy

During this research, using a round-rimmed joystick with 1 vibration motor, an accuracy of 77% (95%CI: 67, 86) was observed for direction-only stimuli and a higher accuracy of 85% (95%CI: 79, 92) was observed for direction-and-proximity stimuli.

This research shows that a very basic round-rimmed joystick, as an active proprioceptive device, can, indeed, be used to seek navigational information. However, it was not as effective of a method to display direction-only stimuli as the passive multi-element and the single-element vibrotactile (belt and wristband, respectively). When it came to direction-and-proximity stimuli, it was as effective as the belt, though less than the wristband.

This research shows that adding more information (proximity) to the stimulus, in the round-rimmed joystick's case, is possible, and does not come at the expense of accuracy whereas in the belt's case accuracy was affected. The accuracy significantly increased for the direction-and-proximity stimuli. This increase in accuracy could be due to two reasons: participants got trained and or the proximity encoded as a pulsation was more effective than intensity change.

Next, the thesis focuses on another aspect of effectiveness. The performance of the round-rimmed joystick in terms of time taken to respond to a given stimulus.

Time-taken

During this research, the mean time taken to respond for stimuli which indicated direction-only was 9.2 (95%CI: 5.7, 12.6) seconds and direction-and-proximity was 10.4 (95%CI: 7.6, 13.2) seconds.

The effectiveness of the round-rimmed joystick in terms of response time was not affected by the addition of proximity information to the stimuli, similar to a wristband which was also not affected by the proximity encoding, whereas in the belt's case, encoding of proximity information came at the expense of increased response time and decreased accuracy.

For the direction-only scenario, the round-rimmed joystick's performance (point estimate: 9.2 seconds) was less than the belt's (point estimate: 4 seconds); and for the direction-and-proximity scenario, the joystick's performance (point estimate: 10.4 seconds) was still less than the belt's (point estimate: 4.9 seconds).

Repeats-taken

During this research, the mean repeats-taken to respond for stimuli which indicated direction-only were 2.8 (95%CI: 1.8, 3.7) repeats per trial and direction-and-proximity were 2.5 (95%CI: 1.5, 3.4) repeats per trial. In other words, participants couldn't confidently report the stimuli on the first exposure and had to confirm the given stimulus by revisiting it a few times: 280 repeats per 100 trials for direction-only and 250 repeats per 100 trials for direction-and-proximity stimuli.

The effectiveness of the round-rimmed joystick in terms of repeats taken was not affected by the addition of proximity information to the stimuli, similar to the belt and wristband.

In comparison to the belt (point estimate: 8 repeats per 100 trials) and the wristband (point estimate: 1 repeat per 100 trials), the joystick's performance in terms of the repeats taken was less: point estimate of 280 repeats per 100 trials for direction-only stimuli and 250 repeats per 100 trials for direction-and-proximity stimuli. These results show a clear difference between the performance of the two passive devices and the active device in terms of exposure rate before a user feels ready to verbally report their response.

This variable of interest hasn't been measured in the published literature.

Next, the thesis focuses on another aspect of effectiveness. The performance of the round-rimmed joystick in terms of experienced workload.

Experienced mental workload

During this research, the mean overall experienced mental workload score, assessed using NASA's Task Load Index (TLX) for stimuli which indicated direction-only was 50 (95% CI: 38, 61) and direction-and-proximity was 60 (95% CI: 45, 74).

The effectiveness of the round-rimmed joystick, in terms of experienced workload, was affected by the addition of proximity information to the stimuli, similar to the belt but unlike the wristband.

The round-rimmed joystick's performance, in terms of the experienced mental workload, was statistically the same as the belt's and wristband's for direction-only stimuli (point estimate: Joystick 50 TLX vs. Belt 29 TLX vs. Wristband 36 TLX) and for the direction-and-proximity stimuli (point estimate: Joystick 60 TLX vs. Belt 47 TLX vs. Wristband 39 TLX).

The effect size based on point estimates clearly shows a difference in the experienced mental workload between the three devices (round-rimmed joystick, belt, and wristband), but statistically, the difference is not significant. This is because of wide confidence intervals due to the sample size used to test each device (n=12). With a larger sample size, the round-rimmed joystick would be the most demanding out of the three devices discussed so far. This will be true for both scenarios: direction-only and direction-and-proximity.

Next, the thesis focuses on another aspect of effectiveness. The performance of the round-rimmed joystick in terms of perceived usability.

System Usability Score

During this research, the mean perceived usability score of a joystick, assessed using Digital Equipment Co.'s System Usability Scale (SUS) for stimuli which indicated direction-only was 66 (95% CI: 54, 79) and direction-and-proximity was 58 (95% CI: 44, 72).

The average perceived usability of the joystick didn't change with the encoding of proximity to the stimuli, the difference is statistically not significant.

Bangor (2009) found in his research that a score of 70 or above indicates good usability for the interface, a score below that indicates marginally acceptable usability, and a score below 50 indicates unacceptable usability for the given interface. Based on this classification, the round-rimmed joystick's perceived usability as an interface for navigation was marginally acceptable.

The perceived usability, based on point estimates, of the joystick was the least usable compared to the belt and wristband for both scenarios (direction-only and direction-and-proximity). However, the perceived usability assessment, similar to the experienced workload assessment discussed, would require a bigger sample size than twelve per device. This will narrow the currently wide confidence intervals and may show a significant difference between the devices.

7.1.4 Haptic Joystick (Octagonal rim)

In this subsection, the thesis looks at the performance of a joystick but with a modification to the rim. This variation was tested to quantify the effect of subtle changes to the stimuli on the performance of a given device. The variation was proprioceptive, related to the rim's shape: this joystick has an octagonal-shaped rim, whereas the previous joystick's rim was round. In terms of vibrotactile cues, there is no difference between any of the three active devices.

In the following subsections, each variable of interest is discussed in turn for the octagonal-rimmed joystick.

Accuracy

During this research, using the octagonal-rimmed joystick with 1 vibration motor, an accuracy of 98% (95%CI: 96, 99) was observed for direction-only stimuli and a slightly lower accuracy of 96% (95%CI: 94, 98) was observed for direction-and-proximity stimuli.

This research shows that a very basic octagonal-rimmed joystick, as an active proprioceptive device, can, indeed, be used to seek navigational information. Moreover, it was as effective of a method to display direction-only and direction-and-proximity stimuli as the passive multi-element and the single-element vibrotactile (belt and wristband, respectively).

This also shows that such a proprioceptive change can have a profound effect on accuracy. The octagonal-rimmed joystick was significantly more effective in terms of accuracy for displaying direction-only as well as direction-and-proximity stimuli than the round-rimmed joystick.

This research shows that adding more information (proximity) to the stimulus, in the octagonal-rimmed joystick's case, is possible, and does not come at the expense of accuracy whereas in the belt's case accuracy was affected.

Next, the thesis focuses on another aspect of effectiveness: the performance of the octagonal-rimmed joystick in terms of time taken to respond to a given stimulus.

Time-taken

During this research, the mean time taken to respond for stimuli which indicated direction-only was 7.6 (95%CI: 5.7, 9.5) seconds and direction-and-proximity was 9.2 (95%CI: 7.0, 11.4) seconds.

The effectiveness of the octagonal-rimmed joystick in terms of response time was affected by the addition of proximity information to the stimuli. Users took longer to ascertain their response to a given stimulus. However, even though the effectiveness of the octagonal-rimmed joystick decreased between the two scenarios (direction-only and direction-and-proximity) in terms of time taken, it was still as good of a performance relative to the round-rimmed joystick during both scenarios. This means that, relative to the round-rimmed joystick, the modification increased the accuracy without a time penalty.

For the direction-only scenario, the octagonal-rimmed joystick's performance (point estimate: 7.6 seconds) was not significantly different than the belt's (point estimate: 4 seconds); and for the direction-and-proximity scenario, the joystick's performance (point estimate: 9.2 seconds) was significantly worse than the belt's (point estimate: 4.9 seconds).

Repeats-taken

During this research, the mean repeats-taken to respond for stimuli which indicated direction-only was 1.6 (95%CI: 1, 2) repeats per trial and direction-and-proximity was 1.4 (95%CI: 1, 2) repeats per trial. In other words, participants couldn't confidently report the stimuli on the first exposure and had to confirm the given stimulus by revisiting it one to two times: 160 repeats per 100 trials for direction-only and 140 repeats per 100 trials for direction-and-proximity stimuli.

The effectiveness of the octagonal-rimmed joystick in terms of repeats taken was not affected by the addition of proximity information to the stimuli, similar to the belt and wristband.

In comparison to the belt (point estimate: 8 repeats per 100 trials) and the wristband (point estimate: 1 repeat per 100 trials, the octagonal-rimmed joystick's performance in terms of the repeats taken was worse: point estimate of 160 repeats per 100 trials for direction-only stimuli and 140 repeats per 100 trials for direction-and-proximity stimuli. These results show a clear difference between the performance of the two passive devices and the active device in terms of exposure rate before a user feels ready to verbally report their response.

This variable of interest hasn't been measured in the published literature.

Next, the thesis focuses on another aspect of effectiveness. The performance of the octagonal-rimmed joystick in terms of experienced workload.

Experienced mental workload

During this research, the mean experienced mental workload score, assessed using NASA's Task Load Index (TLX) for stimuli which indicated direction-only was 32 (95% CI: 21, 43) and direction-and-proximity was 40 (95% CI: 26, 55).

The effectiveness of the octagonal-rimmed joystick, in terms of experienced workload, was affected by the addition of proximity information to the stimuli, similar to the round-rimmed joystick and belt but unlike the wristband.

In comparison to the round-rimmed joystick, the effectiveness of the octagonal-rimmed joystick, in terms of experienced workload, was significantly better for direction-only and direction-and-proximity stimuli. This shows that the improved accuracy of the device was not at the expense of other aspects of effectiveness, i.e., time-taken, repeats-taken, or experienced workload.

The octagonal-rimmed joystick's performance, in terms of the experienced mental workload, was statistically the same as the belt's and wristband's for direction-only stimuli (point estimate: Joystick 32 TLX vs. Belt 29 TLX vs. Wristband 36 TLX) and for the direction-and-proximity stimuli (point estimate: Joystick 40 TLX vs. Belt 47 TLX vs. Wristband 39 TLX).

The effect size based on point estimates clearly shows a difference in the experienced mental workload between the four devices (octagonal-rimmed joystick, round-rimmed joystick, belt, and wristband), but statistically, the difference is not significant. This is because of wide confidence intervals due to the sample size used to test each device (n=12). With a larger sample size, the round-rimmed joystick would be the most demanding out of the four devices discussed so far. This will be true for both scenarios: direction-only and direction-and-proximity.

Next, the thesis focuses on another aspect of effectiveness: the performance of the octagonal-rimmed joystick in terms of perceived usability.

System Usability Score

During this research, the mean perceived usability score of the octagonal-rimmed joystick, assessed using Digital Equipment Co.'s System Usability Scale (SUS) for stimuli which indicated direction-only was 80 (95% CI: 71, 90) and direction-and-proximity was 77 (95% CI: 66, 87).

The average perceived usability of the octagonal-rimmed joystick didn't change with the encoding of proximity to the stimuli, the difference is statistically not significant.

Bangor (2009) found in his research that a score of 70 or above indicates good usability for the interface, a score below that indicates marginally acceptable usability, and a score below 50 indicates unacceptable usability for the given interface. Based on this classification, the octagonal-rimmed joystick's perceived usability as an interface for navigation was good usability for both scenarios (direction-only and direction-and-proximity).

The perceived usability, based on point estimates, of the octagonal-rimmed joystick was the most usable compared to the round-rimmed joystick, belt and wristband for both scenarios (direction-only and direction-and-proximity). However, the perceived usability assessment, similar to the experienced workload assessment discussed, would require a bigger sample size than twelve per device. This will narrow the currently wide confidence intervals and may show a significant difference between the devices.

7.1.5 Haptic Dial

In this subsection, the thesis looks at the performance of a dial as an active proprioceptive vibrotactile display for displaying direction and proximity. This device was tested to quantify the effect of a major change. The major change being the replacement of a thumbstick with a dial. Multiple fingers have to engage in a rotatory fashion, whereas in the joystick's case, it was just the thumb that was engaged. Dial is another widespread component of human-machine interfaces. Examples range from old rotary telephones to control dials in modern cars. Regarding navigation, compasses have dials with directions labelled on them that navigators turn to estimate their heading. A steering wheel is another good example, essentially an oversized dial that the user turns to control the direction of a vehicle.

Finally, in the following subsections, each variable of interest is discussed in turn for the haptic dial.

Accuracy

During this research, using the dial with 1 vibration motor, an accuracy of 94% (95%CI: 89, 99) was observed for direction-only stimuli and a higher accuracy of 98% (95%CI: 96, 100) was observed for direction-and-proximity stimuli.

This research shows that a dial, as an active proprioceptive device, can, indeed, be used to seek navigational information. Moreover, it was as effective of a method to display direction-only as the passive multi-element, single-element vibrotactile and the active proprioceptive vibrotactile devices (belt, wristband, and octagonal-rimmed joystick respectively); for direction-and-proximity stimuli, it was as effective as the passive single-element vibrotactile and the active proprioceptive vibrotactile devices (wristband and octagonal-rimmed joystick, respectively) and more effective than the passive multi-element vibrotactile device (belt).

This research shows that adding more information (proximity) to the stimulus, in the dial's case, is possible, and does not come at the expense of accuracy whereas in the belt's case accuracy was affected.

Next, the thesis focuses on another aspect of effectiveness: the performance of the haptic dial in terms of the time taken to respond to a given stimulus.

Time-taken

During this research, the mean time taken to respond for stimuli which indicated direction-only was 11.5 (95%CI: 8.1, 14.8) seconds and direction-and-proximity was 10.4 (95%CI: 8.5, 12.3) seconds.

The effectiveness of the dial in terms of response time was not statistically affected by the addition of proximity information to the stimuli.

However, for the direction-only scenario, the dial's performance (point estimate: 11.5 seconds) was significantly worse than the belt's (point estimate: 4 seconds); and for the direction-and-proximity scenario, the dial's performance (point estimate: 10.4 seconds) was again significantly worse than the belt's (point estimate: 4.9 seconds). On the other hand, compared to other active devices, the dial was not significantly different, but based on the point estimates, it was the worst-performing active device.

Next, the thesis focuses on another aspect of effectiveness: the performance of the haptic dial in terms of the time taken to respond to a given stimulus.

Repeats-taken

During this research, the mean repeats-taken to respond for stimuli which indicated direction-only were 0.2 (95%CI: 0.05, 0.41) repeats per trial and direction-and-proximity were 0.2 (95%CI: 0.04, 0.31) repeats per trial. These numbers show that stimuli were not recognised on the first exposure: 20 repeats per 100 trials for both scenarios (direction-only and direction-and-proximity).

The effectiveness of the dial in terms of repeats taken was not affected by the addition of proximity information to the stimuli, similar to the belt and wristband.

In comparison to the belt (point estimate: 8 repeats per 100 trials) and the wristband (point estimate: 1 repeat per 100 trials), the dial's performance in terms of the repeats taken was worse: point estimate of 20 repeats per 100 trials. These results show a clear difference between the performance of the two passive devices and the active dial in terms of exposure rate before a user felt ready to verbally report their response.

However, in comparison to the other active devices (both joysticks), the dial was significantly better during both scenarios (direction-only and direction-and-proximity).

This variable of interest hasn't been measured in the published literature.

Next, the thesis focuses on another aspect of effectiveness. The performance of the dial in terms of experienced workload.

Experienced mental workload

During this research, the mean experienced mental workload score, assessed using NASA's Task Load Index (TLX) for stimuli which indicated direction-only was 56 (95% CI: 47, 65) and direction-and-proximity was 59 (95% CI: 46, 72).

The effectiveness of the dial, in terms of experienced workload, was not affected by the addition of proximity information to the stimuli, similar to the wristband but unlike both joysticks and the belt.

The dial's performance, in terms of the experienced mental workload, was statistically worse than the belt's and octagonal-rimmed joystick for direction-only stimuli (point estimate: belt 29 TLX, octagonal-rimmed joystick 32 TLX) and for the direction-and-proximity stimuli there was no significant difference found between the devices (point estimate: belt 47 TLX, octagonal-rimmed joystick 40 TLX).

The effect size based on point estimates clearly shows a difference in the experienced mental workload between the five devices (octagonal-rimmed joystick, round-rimmed joystick, belt, and wristband), but statistically, the difference is not significant. This is because of wide confidence intervals due to the sample size used to test each device (n=12). With a larger sample size, the round-rimmed joystick and the dial would be the most demanding out of the five devices discussed. This will be true for both scenarios: direction-only and direction-and-proximity.

Next, the thesis focuses on another aspect of effectiveness: the performance of the dial in terms of perceived usability.

System Usability Score

During this research, the mean perceived usability score of the dial, assessed using Digital Equipment Co.'s System Usability Scale (SUS) for stimuli which indicated direction-only was 59 (95% CI: 49, 68) and direction-and-proximity was 59 (95% CI: 48, 71).

The average perceived usability of the dial didn't change with the encoding of proximity to the stimuli, the difference is statistically not significant.

Bangor (2009) found in his research that a score of 70 or above indicates good usability for the interface, a score below that indicates marginally acceptable usability, and a score below 50 indicates unacceptable usability for the given interface. Based on this classification, the dial's perceived usability as an interface for navigation was marginally acceptable for both scenarios (direction-only and direction-and-proximity).

The perceived usability of the dial, based on point estimates, for direction-only, was the lowest scored compared to other devices tested; and for direction-and-proximity, the dial, round-rimmed joystick, and the belt were dimmed marginally acceptable in terms of usability.

Statistically, devices didn't show a significant difference in terms of usability. However, similar to the experienced workload assessment discussed, the perceived usability assessment would require a bigger sample size than twelve per device. This will narrow the currently wide confidence intervals and may show a significant difference between the devices.

7.2 Discussion

This section delves into seven key themes that emerged from the investigation of five haptic displays in the context of navigation. These themes shed light on the multifaceted nature of haptic displays and their impact on user preferences, experiences, and practical applications. In the following subsections, each theme is explained with its implications, challenges, and potential avenues for future research and development.

7.2.1 One size does not fit all

In the domain of haptic interfaces, it becomes evident that one size does not fit all when considering objective performance and subjective user preferences. Various factors come into play, such as the physical size of devices, haptic stimuli design, and several other attributes such as passive versus active, single-element versus multi-element, and body parts involved.

The physical size of haptic devices plays a crucial role in user experience. Different users may have different ergonomic requirements and body shapes and sizes, which can impact their ability to interact with the device comfortably and effectively. Therefore, customisation options and adjustable features become essential to accommodate individual differences. For example, during this research, the haptic belt actuators were adjustable to move around to accommodate varying waist sizes across the participants. On the other hand, for example, where the design lacked such adjustability, several participants (5 out of 12) mentioned difficulty using the dial because the dial was small in size or its notch was not prominent enough.

Additionally, the design of haptic stimuli is a critical aspect that influences user perception and engagement. Different users may respond differently to various tactile patterns, vibration intensities, modes of operation, or forces applied by the haptic interface. Personal preferences and sensitivities come into play, and the design needs to consider a wide range of user preferences to ensure an optimal user experience. For example, during this research, it was found that just changing the contour of the rim for the joystick (round-rimmed versus octagonal-rimmed) significantly affected the objective performance and user experience. On the other hand, in the case of the haptic belt, proximity was represented as a weak or strong intensity which led to multiple participants (4 out of 12) mentioning difficulties with intensity, either finding it too tickly or not different enough.

Modes of operation also play a significant role in haptic interfaces. Passive haptic devices provide pre-defined feedback without requiring user input, while active haptic devices allow users to actively engage and manipulate the feedback they receive. The choice between these modes depends on the specific application and user requirements. For example, a thumbstick-based active proprioceptive display proved, objectively and subjectively, as effective as a belt in the context of navigation, however, may not be in another application such as haptically communicating emotions (Buimer et al., 2018). As another example, the haptic wrist band was the most preferred and objectively effective display in a seated psychophysical setting, but may lead to issues in a realistic setting; for example, mentioned by a visually impaired during a demonstration meeting, with a mobile phone-based haptic navigation, they had to turn around until they were facing the desired orientation to receive a haptic confirmation of the correct direction. However, this method often led to dizziness and self-consciousness due to the frequent whole-body turns required. The thumbstick-based joystick would allow them to discreetly scan for the correct orientation by simply turning their thumb and avoiding both issues.

Similarly, the distinction between single-element and multi-element haptic devices offers different possibilities in terms of feedback richness and complexity. The same argument applies here, single-element haptic wristband performed well as a navigational display in a psychophysical setting, but a multi-element may prove to be more effective in communication applications where complex ideas are to be communicated.

Considering these diverse factors, it becomes clear that a tailored approach is necessary to address the varying needs and preferences of users. A one-size-fits-all approach may not provide the desired outcomes in terms of both objective performance and subjective user satisfaction. Future research and development should focus on customisable haptic interfaces that allow users to personalise the experience, adapting to their individual preferences and requirements.

7.2.2 Multi-disciplinary approach

Haptic technology encompasses a vast field with diverse applications ranging from telesurgery and gaming to navigation. Within this broad spectrum, a wide array of actuators and techniques are employed, highlighting the multidisciplinary nature of haptic research. Embracing a multi-disciplinary approach can foster creative and effective solutions.

This research explored the potential of repurposing gaming joysticks as haptic displays for navigation rather than limiting them to their traditional role as input devices for gaming consoles. This innovative approach allowed us to leverage existing technology and adapt it for a different purpose, showcasing the versatility of haptic interfaces. By modifying and hacking the joysticks, this research transformed them into effective haptic devices, capable of providing intuitive navigational cues.

To evaluate the user experience of these devices, this research drew inspiration from the field of human factors. It incorporated methodologies commonly used in human factors research, such as subjective assessments and user-centred evaluations. The inclusion of well-established assessment methods like the NASA Task Load Index (TLX) and System Usability Scale (SUS) allowed for standardised measurements, facilitating meaningful comparisons and future replication studies.

One notable finding from this research was the preference of several participants for the octagonal joystick among the five different devices tested. Not only did it receive positive subjective feedback, but it also demonstrated promising quantitative performance. This valuable insight opens up possibilities for its application in assistive technologies. For instance, incorporating the octagonal joystick into a white cane, as shown in Figure 7.2, could enhance the navigational experience and accessibility for individuals with visual impairments.

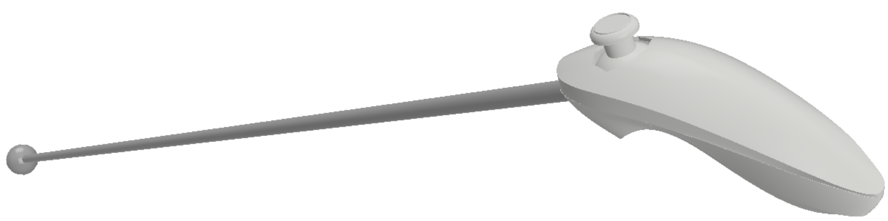

Figure 7.2: Representational image of a cane with a thumbstick integrated in the handle

Overall, the multi-disciplinary approach enabled this research project to explore the potential of haptic technology across different domains, repurpose existing devices creatively, and thoroughly evaluate the devices. By leveraging the strengths of each discipline, we can drive innovation, standardise methodologies, and ultimately advance the field of haptic research.

7.2.3 Demonstrations and potential users' feedback

Demonstrating prototypes to potential users for their feedback is a crucial step in the development process. This research recognised the importance of engaging both sighted individuals and those with visual impairments to gather valuable insights and suggestions for improvement.

During the prototype demonstrations, we had the opportunity to showcase our haptic devices to a diverse group of people. Among them were visually impaired individuals who provided particularly encouraging and insightful feedback. For instance, when the joystick was presented as a haptic display to a visually impaired person, they immediately recognised its potential for ball tracking during golf. They even suggested replacing the joystick with a dial as an improvement. A similar suggestion for exploring a dial-based prototype was also made by an attendee during a presentation to a sighted group of people. A haptic dial was tested during this research as a result of such inputs, highlighting the value of user perspectives.

In another demonstration session with a visually impaired person, an issue related to a mobile phone-based haptic navigation system was mentioned. They mentioned that in order to receive haptic confirmation of the correct direction, they had to turn around until they were facing the desired orientation. However, this method often led to dizziness and self-consciousness due to the frequent whole-body turns required. Recognising this issue, the thumbstick-based octagonal joystick or the haptic dial could be a promising option as it would allow discreet scanning for the correct orientation by simply turning the thumb. This would alleviate both the issue of dizziness and the self-consciousness associated with extensive whole-body movements.

The feedback and suggestions received during these prototype demonstrations proved invaluable to this research. Engaging with potential users, both visually impaired and sighted, not only provided fresh perspectives but also identified potential applications, highlighted areas for improvement, and brought attention to usability concerns. By actively involving users and incorporating user insights into the design and development process, haptic devices can be created that are inclusive, intuitive, effective, and tailored to the needs of the end-users that address real-world challenges.

7.2.4 Dynamic nature of haptic preferences

In line with the famous quote by Howard Moskowitz, an American market researcher and psychophysicist, who stated that 'The mind knows not what the tongue wants', this research shows that the same could be said about haptic preferences, they are not solely determined by our conscious preferences or expectations. Similar to our sense of taste, our brain and skin receptors may respond positively to haptic stimuli that we may not initially expect or think we would prefer.

During this research, an interesting finding emerged: out of the 12 participants, 5 participants (42%) expressed a change in their preferences for the haptic displays over the sessions. This suggests that conscious preferences or expectations were updated based on the actual experience of testing each prototype. At the same time, in the case of 7 participants (58%), their initial preferences were validated and remained unchanged. This underscores the notion of user-centred design as well as one-size-does-not-fit-all. Our haptic preferences are nuanced and may evolve through direct interaction with the prototypes. The brain and skin receptors respond in ways that might surprise us, indicating that our initial expectations may not align with the actual experience.

7.2.5 The optimal choice of display

In the quest to identify the optimal haptic display for a given context, it is crucial to consider both the quantitative optimal choice for the general population and the importance of facilitating individuals in finding their personal qualitative optimal choice. While determining the quantitative optimal choice provides valuable insights, enabling users to discover their preferred haptic display at a personal level is equally important.

For example, during this research, the quantitative optimal choice for the group of 12 participants in the navigational context was a haptic wristband. However, individual preferences emerged as a compelling aspect of the study which were captured by the qualitative analysis. Out of the 12 participants, 4 individuals (33%) expressed a preference for one of the active devices after testing all five prototypes. Specifically, 2 participants favoured the octagonal-rimmed joystick, while the other 2 participants preferred the dial. These findings highlight the subjective nature of haptic preferences, where personal inclination can influence the choice of a preferred device. These findings were realised through qualitative data.

Interestingly, 4 participants modified their preference after experiencing all five prototypes, shifting from active to passive devices, while 1 participant transitioned from a passive to an active device. These changes in preference demonstrate the importance of exposing users to a diverse range of haptic displays. By allowing individuals to explore various options, the selection process becomes individualistic, fostering a sense of agency and increasing the likelihood of technology adoption.

In short, while identifying the quantitative optimal choice of haptic displays is important in a given context, enabling users to find their personal optimal choice is equally crucial. By exposing users to diverse displays and supporting individual preferences, we may promote technology adoption and create a more personalised and satisfying haptic experience.

7.2.6 Issues with the right approach

Facilitating an individualistic selection process for haptic displays poses certain challenges due to the extensive variety of haptic display profiles and the impact of subtle design changes on performance and user experience. As discussed in Chapters 1 and 2, haptic displays encompass a range of attributes including type (e.g., Vibrotactile, Electrotactile, Thermotactile, or Mechano-tactile), variation (e.g., single-element or multi-element), operational mode (e.g., active or passive), and form (e.g., grounded, ungrounded, wearable, or handheld). Additionally, even slight variations in haptic stimuli design can have a significant influence on the overall performance and user preference of a specific haptic display.

For instance, in this research, a comparison was made between a round-rimmed haptic joystick and an octagonal-rimmed haptic joystick. The distinction was subtle, focusing on the contour of the rim, yet the consequence was remarkable. The round-rimmed variant emerged as the least preferred choice, while the octagonal-rimmed variant was among the most preferred. In terms of objective performance, a similar trend exists, the octagonal-rimmed joystick performed significantly better than the round-rimmed joystick across many variables of interest, such as accuracy, number of repeats taken, experienced workload, and perceived usability. This highlights the significance of considering even minor design elements when developing haptic displays to align with user preferences.

Considering the vast array of haptic devices and stimuli designs, facilitating optimal solutions and selection processes becomes a significant undertaking. However, it can be accomplished by employing various approaches. One such approach is cross-disciplinary collaborations across disciplines, institutes, and sectors, exemplified by initiatives like the European Union's Horizon 2020 funded project called SUITCEYES. By fostering partnerships between academia, public organisations, and private/commercial entities, innovative solutions and diverse haptic displays can be explored.

Furthermore, embracing open-data and open-science philosophies, along with standardised methodologies for data collection, analysis, and sharing, can enhance the efficiency and transparency of haptic research. Well-equipped laboratories with a diverse range of haptic displays, including novel as well as off-the-shelf, recycled, and repurposed devices, can provide researchers and users with a comprehensive testing environment.

Additionally, using modular design principles would enable faster prototyping of different haptic display profiles. This modular approach streamlines the iterative design process, allowing for rapid exploration and customisation to meet individual user requirements.

Furthermore, the integration of data science and machine learning tools, such as optimisation algorithms and neural networks, can play a pivotal role in facilitating the selection process. Similar to the recommendation engines employed by platforms like Netflix and Spotify, tailored recommendations for haptic displays could be generated based on user preferences and performance data. This personalised approach maximises the chances of identifying the optimal haptic display for an individual user.

Therefore, while the diversity of haptic display profiles and the impact of design variations present challenges, various concepts and approaches can be employed to facilitate an individualistic selection process. Cross-disciplinary collaborations, open-data and open-science philosophies, standardised methodologies, well-equipped laboratories, modular designs, and data science tools can all contribute towards enhancing the effectiveness, personalisation, and user satisfaction in the field of haptic technology.

7.2.7 Refinement, inclusion, and realistic navigational tasks

This research project has evaluated five haptic prototypes in the context of navigation. The haptic display prototypes were used to effectively receive (passive) or seek (active) navigational instructions. However, it is important to acknowledge that realistic navigational tasks encompass a multitude of factors, including memory, mental maps, spatial frames of reference (such as egocentric and allocentric systems), as well as training and learning effects.

The evaluation of haptic prototypes in this research serves as an initial step towards their refinement and further inclusively evaluating their efficacy with diverse participants in realistic scenarios. Such scenarios could involve navigating from one point to another, both indoors and outdoors, while considering factors such as obstacle avoidance and determining relative orientation. To achieve this, realistic scenarios can be set up in either the real world or within virtual, or even augmented or mixed, reality environments. Virtual reality offers a controlled setting to test devices in simulated outdoor or indoor settings, providing both safety and comfort within a laboratory environment.

The goal of testing haptic devices in these realistic scenarios is to deepen our understanding of their performance and effectiveness. By subjecting the prototypes to diverse and challenging navigation scenarios, we can gather valuable insights that will inform further improvements. This iterative process of refinement and evaluation will contribute to the development of effective and intuitive navigational displays that cater to the needs of potential users.

Ultimately, the findings and refinements derived from this research will serve as stepping stones towards the next stage of evaluation and the eventual commercialisation of haptic displays for navigation. By thoroughly investigating their performance in realistic scenarios and ensuring inclusivity in participant evaluation, we can enhance our understanding of haptic technology and bring forth navigation solutions that are effective, intuitive, and user-centric.

7.3 Conclusions

This research set out to evaluate and compare the effectiveness and intuitiveness of two different methods of haptically displaying navigational information to the user. The two methods were passive vibrotactile and active proprioceptive vibrotactile. Each method was evaluated independently and then compared to each other. To thoroughly evaluate passive vibrotactile as a method, two types of passive vibrotactile devices were used: a single-element wristband and a multi-element belt. On the other hand, active proprioceptive vibrotactile as a method was evaluated using two thumb-controlled joysticks and another device with a rotatory dial. Below are the conclusions of this research.

The first sub-research question, targeting knowledge-gap-1, was: how effective and intuitive is a passive single-element vibrotactile wristband (compared to a passive multi-element vibrotactile belt) for displaying navigational information? This research has shown that passive single-element display is as, and in some aspects more, effective and intuitive as the haptic belt. Based on the quantitative results as well as the informal interviews, a single-element vibrotactile display, which was a haptic wristband, is not inferior to a multi-element vibrotactile display, which was in the form of a belt, in the given context. Figure 7.3 and Figure 7.4 represent the statistical differences detected using t-tests for both scenarios.

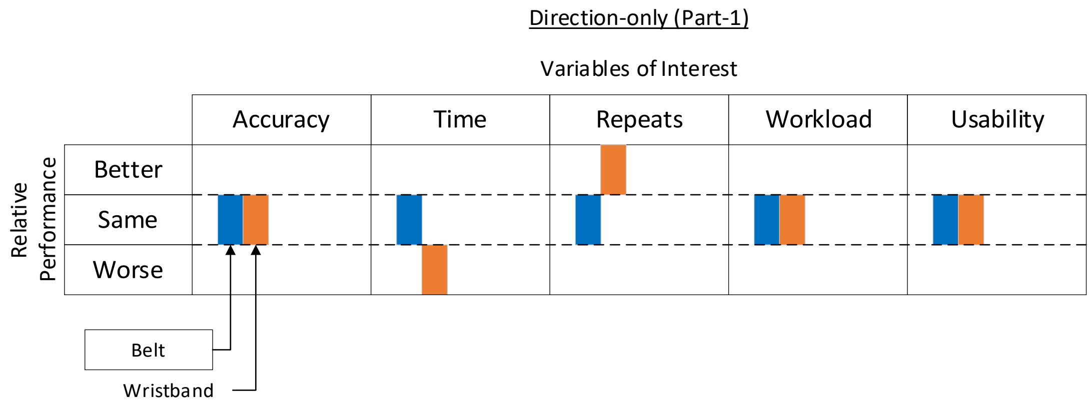

Figure 7.3: Statistical differences detected among passive displays (using t-tests) for the direction-only scenario

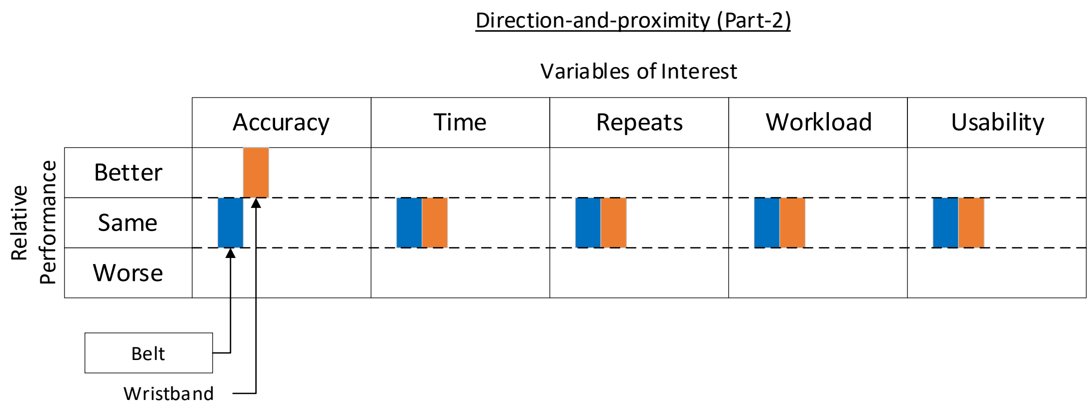

Figure 7.4: Statistical differences detected among passive displays (using t-tests) for the direction-and-proximity scenario

The second sub-research question, targeting knowledge-gap-2, was: how effective and intuitive is an active proprioceptive vibrotactile device for displaying navigational information to the user? This research has shown that active proprioceptive displays can be used to display navigational information effectively and intuitively. This research has shown that subtle changes to the active proprioceptive interface can result in significant gains or losses in performance across different aspects. Figure 7.5 and Figure 7.6 represent the statistical differences detected using t-tests for both scenarios.

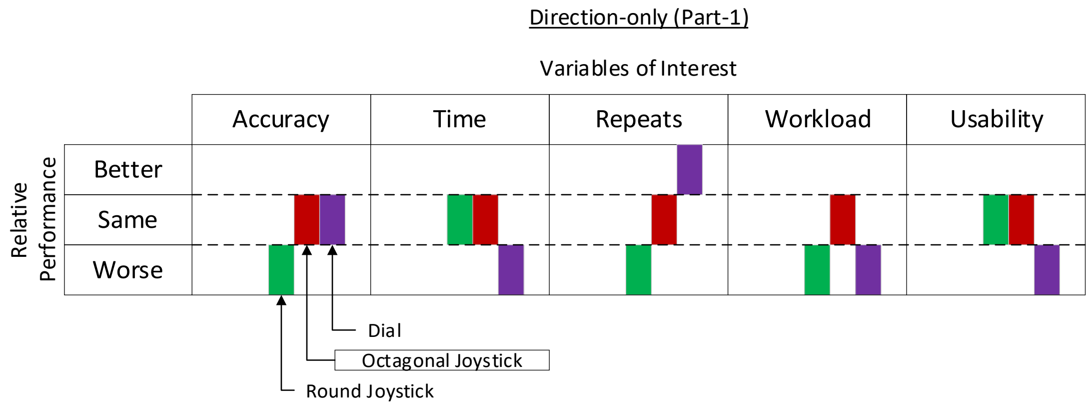

Figure 7.5: Statistical differences detected among active displays (using t-tests) for the direction-only scenario

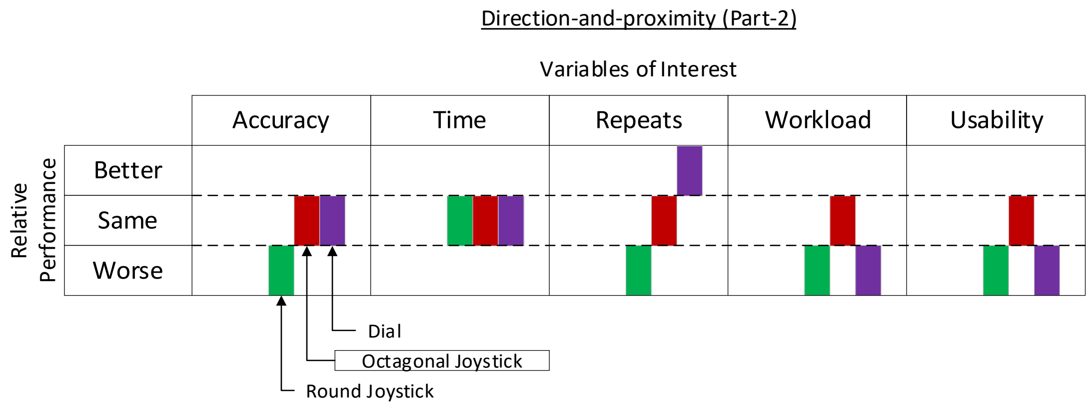

Figure 7.6: Statistical differences detected among active displays (using t-tests) for the direction-and-proximity scenario

Finally, the main research question, targeting the knowledge gaps-3 to 5, was: how intuitive and effective is an active proprioceptive vibrotactile device compared to a passive vibrotactile device for displaying navigational information to the user? This research demonstrates that active proprioceptive displays can effectively and intuitively convey navigational information. The performance of active devices compared to passive devices varies depending on the specific variation of the device and the performance aspect being considered. The summary of statistically significant differences detected using ANOVA and post-hoc Tukey's (HSD) analysis is given in Figure 7.7 and Figure 7.8.

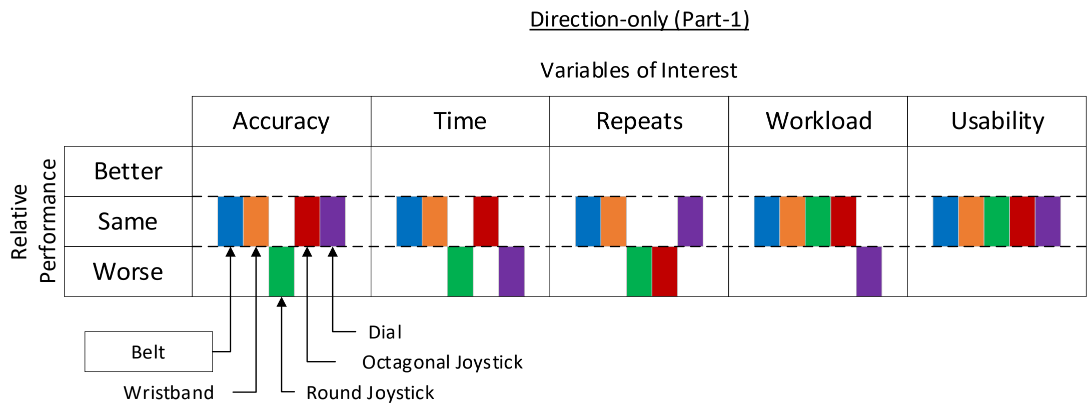

Figure 7.7 Summary of statistical comparisons to the belt for the direction-only part

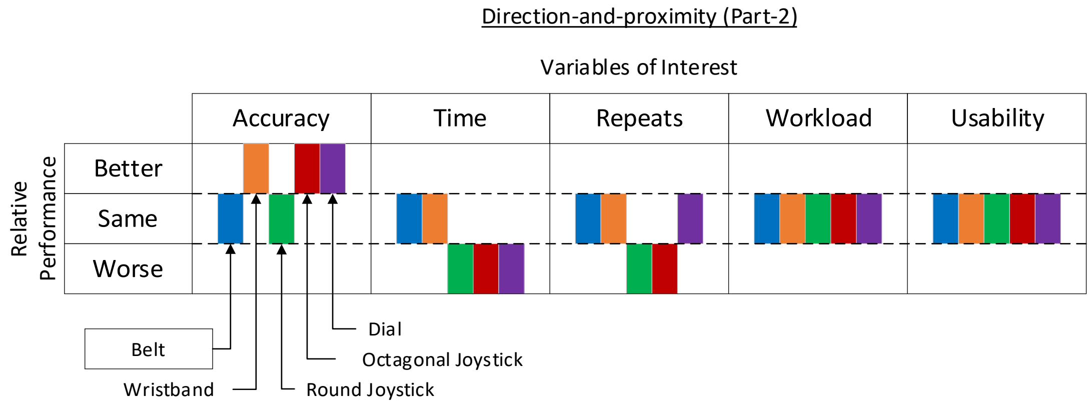

Figure 7.8 Summary of statistical comparisons to the belt for the direction-and-proximity part

7.3.1 Contributions

As a recap and declaration, this study has made the following contributions to the body of knowledge:

- Results of a thorough multi-aspect evaluation of a passive single-element vibrotactile-based haptic display for navigation.
- Results of a thorough multi-aspect evaluation of a passive multi-element vibrotactile-based haptic display for navigation.
- Results of a thorough multi-aspect evaluation of active proprioceptive vibrotactile-based devices as haptic displays for navigation.

- The effect of subtle changes to haptic cue design: round-rimmed joystick versus octagonal-rimmed joystick.
- Results of a comparative analysis of different displays which were based on two different methods.
- Results that can serve as a benchmark for evaluating and comparing other designs and methods for displaying navigational information.
- Introducing a methodology for evaluating and comparing haptic displays used for communicating navigational information, which can be utilised by other researchers to test their prototypes and compare their results with those obtained in this research and other studies.

7.3.2 Actionable takeaways

This study evaluated a single-element vibrotactile haptic display for navigation, using multiple criteria. The main findings were that such a device, similar to a smartwatch, can provide navigational cues effectively. It can indicate not only basic directions (left, right, forward), but also more nuanced ones (e.g.,10 o'clock, 11 o'clock). It can also communicate distance information (near, far). The study demonstrated that a single-element haptic display is not worse than a multi-element one in the given context. Interview results show that it was the most preferred device. Additionally, the study gathered user suggestions for further improvements. One recommendation based on the user feedback being allowing users to adjust the intensity levels to represent different distances. The study proved that the device and the haptic cues are intuitive and efficient in a psychophysical setting, and proposed the next step of testing them in a real-world navigational task where participants (including participants with impairment) would have to move from one location to another while collecting data on various variables of interest.

Regarding passive multi-element vibrotactile belt, this study shows, in line with the published body of research, that it can effectively and intuitively display navigational information. Specifically, time-taken performance of the belt was better than other devices. However, moving forward more work needs to be focused on the physical aspects of the belt, e.g., making the haptic belt more comfortable to wear and highly customisable particularly in terms of actuator positions and easily adjustable intensity options. Haptic belt should also be used to explore reliable generation of phantom effects (explained more in the section 7.3.3) to convey navigational information.

This study has demonstrated that active proprioceptive vibrotactile devices, such as Haptic joysticks (especially the octagonal joystick) and the dial, can effectively and intuitively convey navigational information. And that this method is comparable to a haptic belt which has shown to perform well in the published literature. The study also shows that the design of the interface that engages the sense of proprioception matters a lot in terms of its quantitative and qualitative performance. For example, the octagonal-shaped contour for the stick dramatically increased the performance of the device compared to a round-shaped contour and a dial interface. Physical landmarks aid the sense of proprioception to an extent that even slightly different positions of the thumb, or a dial, could reliably be mapped to a set of directions. Furthermore, joysticks are based on dual-axis potentiometers. Potentiometers are cheap, lightweight, and small requiring very little power to operate. These characteristics lend themselves to integration of this component into other devices such as white cane's handle (as shown in Figure 7.2) or wearable bands. Finally, the performance of active proprioception should be tested in a realistic navigational task as next step. And incorporating users' comments, noted during the interviews, may further increase the performance, for example, dead-ends for the sticks and dial, more prominent notches designed into the contour, customisable intensity settings such as strength of the intensity, or frequency of the pulsation.

This research has used objective and subjective measures to evaluate device's performance. Furthermore, exposed users to multiple devices. This approach is a user-centred approach as it can detect differences beyond objective performance. For example, the wristband, octagonal joystick, and dial were not significantly different in terms of accuracy, however, dial scored significantly higher for experience mental workload as compared to both the wristband and the octagonal joystick. However, during interview-based ranking of the devices, two out of 12 participants yet ranked dial as their preferred choice of device for the given task. Methodology used during this research shows that the improvement of haptic devices will require a detailed evaluation of prototypes for a given application.

7.3.3 Limitations

This research has certain limitations which are important to explicitly list. The identified limitations are as follows:

The sample size (n=12) proved inadequate for some measurements in terms of the power of the study. A smaller sample size, for some aspects of the performance, led to wider confidence intervals leading to overlapping ranges and, therefore, non-significant results. Other issues that can arise from smaller sample sizes are generalisability and sampling bias due to the participant selection process not being truly random.

Seated psychophysical tests of the haptic prototypes are one piece of the overall picture. This research did not go further to test them in practical and realistic scenarios of physically navigating a space using these prototypes. A full understanding of these methods and haptic prototypes requires the next step.

The performance of haptic prototypes was measured with minimal training. Participants were verbally briefed on how to use the given device, followed by one round of introductory exposure to the stimuli. Therefore, the results represent performance without training and explicit learning factors. In real-life scenarios, both form an important part of the performance and adoption of any device.

The concept of mental maps hasn't been explored during this research. Mental maps are an important concept in the context of navigation. Whether any of the methods or prototypes led to inferior or superior mental maps was not explored.

One important application of haptic displays is their use as assistive devices for navigation by deafblind and blind individuals. In this research, experiments were conducted where sighted and hearing participants were blindfolded and wore earmuffs. However, it is important to note that the results from these experiments cannot be assumed to accurately represent the performance of deafblind and blind users without specifically testing the methods and prototypes with them.

These limitations can be addressed which will be discussed in the following section.

7.4 Future-Research

The findings of the current research, along with its limitations, provide a foundation for recommendations aimed at advancing the understanding of haptic displays in the context of navigation. These recommendations should be incorporated into future research endeavours to further enhance our knowledge in this field. Below are a few recommendations to consider:

The prototypes tested in this research should be further tested in **realistic tasks**; for example, how effective and intuitive are given haptic displays, and associated haptic cues and methods, in aiding the user to physically navigate a space from one point to another? It is crucial to investigate how well these haptic displays facilitate movement from one point to another, providing valuable insights into their practical application and user experience in real-world scenarios. This aspect of evaluation will contribute to a more comprehensive understanding of the prototypes' capabilities and their potential for assisting individuals in navigation tasks. Furthermore, this will also allow us to understand the change in performance between psychophysical tasks and realistic-application tasks. This understanding will allow us to answer another interesting question: Can we assume a device’s real-world performance based on psychophysical testing results? Incorporating this point in future research will ensure a further understanding of the capabilities and practicalities of haptic displays in navigation tasks.

During this research, each participant was informally interviewed after each test. There were five devices and 12 participants which amounted to 60 tests in total. In these interviews, participants made interesting **suggestions for design improvements**. To further improve the designs of the tested prototypes and measure their effect on the performance would be highly recommended to form part of future research. By incorporating these suggestions and evaluating their impact, the studies can contribute to the advancement and optimisation of the haptic prototypes' design, usability, and functionality. Such improvements could lead to more refined and effective haptic displays.

One of the key user groups for haptic displays for navigation is the deafblind and blind population. This research tested the prototypes with sighted and hearing participants who were blindfolded and wore earmuffs. One of the limitations mentioned earlier was that, maybe, we cannot assume the results to be representative of the aforementioned group. Most of the published work focusing on haptic displays for navigation as assistive devices recruit sighted and hearing participants and simulate deaf-blindness using blindfolds and earmuffs. If the current research findings are categorised as results of a control group, then we can repeat the **testing with deafblind and blind participants** as a treatment group to answer another interesting research question: Is there and how much of a difference exists between the two groups, given a haptic display for navigation? Incorporating this point in future research would enhance the understanding of how haptic displays for navigation perform and benefit deafblind and blind users, addressing an important aspect of their accessibility and assistive technology needs.

The **effect of learning** was not covered by this research. In fact, it was intentionally restricted in order to measure baseline performance while keeping the influence of learning as little as possible; this research achieved that by keeping the training or introduction to haptic cues minimal. However, now that a baseline has been established for the tested devices, in future research, the learning curves for each device can be quantified and its effect on different aspects of performance, in the context of navigation, could be investigated. Such research will lead to a further understanding of improvements in performance over time through learning.

In realistic navigational activities, **mental maps** play an important role. Their construction is based on perception, experiences, and memory of the environment. During this research, as the testing was psychophysical in nature, the mental maps were not relevant. However, as the next step would be to test the devices in practical realistic navigational scenarios, the influence, or lack of it, of any given device on the mental maps would become very relevant and worthwhile investigating to further increase our understanding of haptic devices' role in navigation.

Other research efforts can deploy the **methodology** used during this research as is, similar, or further improve it to quantify the performance of haptic prototypes in the context of navigation or in general. Such **standardisation** will help with the **meta-analysis** of published research in terms of enhanced comparability and compatibility of the data, reduction of heterogeneity, and increased statistical power.

Finally, an important concept of **phantom effect** in haptics has not been explored during this research, however, should be explored in the future research projects. Phantom effects are considered a promising approach to provide complex sensations through simple actuation paradigms (Lacôte et al., 2023). It is a phenomenon where users experience touch sensations on their bodies even though no physical contact has occurred. This effect is commonly reported by users of haptic devices. These effects range from cutaneous rabbit (where three actuators can cause a feeling of an illusory rabbit climbing from the position of first tractor to the third) and creation of sensation between just two stimulation points to well-defined flow-like sensations using a multi-element belt like devices (Hayward, 2008; Choi and Kuchenbecker, 2013). Researcher are trying to use this concept in applications such as sensory-aid displays, tactile communication, haptic navigation displays, and human-computer interfaces (Rahal et al., 2009; A. Adilkhanov et al., 2022; Lacôte et al., 2023).

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