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Graduation Project for Creative Technology

Designing a haptic wearable for people with visual impairment to aid navigation

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Abstract

Within this paper, the development of a haptic wearable device, utilizing vibration patterns is documented. The device was developed for people with visual impairment to aid them in their navigation efforts. Specifically, the project aims to help users to gain an understanding of their larger surroundings, to do informed and safe decisions, and to enable them to navigate within new environments, looking for doors, stairs and other important objects. Within three major iterations, user related design criteria were collected and matched with technical elements to create a device capable of telling the environment in front of the user to the user and to provide more information about the nature of certain obstacles. Users were considered during the development and the device was designed with their needs in mind. The device did not aim to replace common aids, such as the cane. It utilizes input from a computer vision sensor developed by a team member as input. It consists out of a vest, which is capable telling the user what is in front of him through haptic symbols, and a gauntlet which utilizes tactons to symbolise certain types of objects if needed to provide more detailed information. In addition, a universal haptic language was developed, which could potentially be used in other projects. The system was tested with visually able people in several tests to great success. The result is a promising prove of concept, which offers already deeper insights into the development of such a device.

Contents

Chapter 1

Introduction

Navigation can be difficult for some people. Even more so for people who are suffering from a form of visual impairment. Conventional navigation systems for people with visual impairment have a number of weaknesses, especially in busy or unfamiliar scenarios (Toro et al., 2020). Beyond that visual or audio based navigation systems are often difficult to use. These information interfaces can cause a great deal of confusion or distraction for visually able and impaired users alike, as they require a large degree of focus on these senses for orientation in the real world. In some scenarios they can even prove to be entirely unusable. Examples of this are very chaotic situations, such as for soldiers in war zones or firefighters in duty (Prasad et al., 2014).

A possible solution to this issue can be the application of haptic information interfaces. Haptics usually refer to the use of vibration or pressure actuators which are in contact with users skin to convey information alone or in combination with other information interfaces. They have the potential of offering a low mental strain support for navigation in situations where navigation might be difficult. A large number of papers have focused on trying to develop haptic wearables for exactly these situations with the goal of conveying information without interfering with other essential senses (Paneels et al., 2013).

This graduation project will focus on the design and initial development of a haptic navigation device for people with visual impairment. The goal is to use the benefits which haptic navigation promises, especially for people with visual impairment, to create a device which holds the potential to be of use for people with visual impairment in certain situations, in which these users still have problems to navigate. This graduation project is being developed together with two other students, namely Tim Yeung and Kai Ferdelman. The group-research question is as follows: *How to design a wearable to enhance the navigation capabilities of* *people with a visual impairment using haptics?*. It focuses on how to design a haptic wearable to enhance the navigation capabilities of people with visual impairment. To answer it, the group work is split up into three individual graduation projects which focus on the sensing, the actuation and a virtual testing environment, each with individual research questions.

This graduation project will specifically focus on the actuation and the design of the wearable device for the user leading to the research question *How to design a wearable that gives haptic information for navigation for people with visual impairment?*

To answer this, the research question will be divided into the following sub-research questions: (1) What are relevant factors that contribute to the effectiveness of haptic communication? (2) What are relevant factors that contribute to the intuitiveness of haptic communication? (3) What are criteria of usability for a haptic navigation device for people with visual impairment? (4)Which forms of haptic stimulation are suitable for encoding information ? (5) What are the qualities of different forms of haptic stimulation?

These questions aim to address a number of goals. (1) aims to develop criteria which influence the successful understanding of transmitted information and how these criteria can be used to improve the performance of a haptic navigation device. (2) aims to develop criteria which support the intuitive perception of information transmitted through haptics. (3) aims to develop criteria which support the development for the specific target group. (4) aims to create an overview over different technical and code solutions which currently have been researched or employed. (5) aims to develop deeper insights into these different solutions and how their unique characteristics and qualities can be used to improve or otherwise influence the development of a haptic navigation device. This includes technical qualities, as well as qualities perceived by user during tests.

1.0.1 Relevance

While there already a few devices which aim to achieve similar goals, none have so far successfully managed to impact the lives of people with visual impairment. During our research interviews with users we found that there are some drawbacks to many available technical aids. This is due to a number of problems which are not being addressed by these devices. Especially not in their entirety. Some aids fail to address the real needs of users with visual impairment, providing unnecessary information in some cases or to little in others. Some even seem to attempt to replace common aids such as the white cane without offering the same cost to function ratio, as has been found in one user interview, making them not a viable alternative. Also longevity and the support of health insurances are important to enable users to do a justified purchase according to van Hasselt (2021). Additionally, some users feel cluttered or discriminated by some of the devices, according to our interviews.

The project, this graduation project is connected to gains relevance by acknowledging these issues and include them in the design process to develop a prototype, which has its users and specific use case in mind. How these issues will influence the design decisions made for this project will be detailed throughout this report.

Chapter 2

Background research

Before the ideation and design phase can happen, the background, as well as the end user have to be considered. Therefore, this research focuses on learning about the user group, its needs and its challenges, as well as the current state of the field and research results of derived from the design processes and users tests of other researchers within this field of research. This information can be translated into design criteria which will then in later chapters influence the concept and design of the prototype. To acquire this information a literature review, an Interview with the accessibility advisor Timon van Hasselt and a number of interviews with members of the target group were conducted.

2.1 State of the art

The state of the art, as far as researched, mostly consists of devices which serve more as prototype devices to research working principles of haptic navigation or devices meant as a demonstration for certain design factors. Only very few commercially available products which classify as haptic wearables and aim to support the community of people with visual impairment have been found. None seem to influence the market in any significant way. This selection was expanded during the interviews conducted, such as with Timon van Hasselt (2021), but also others, who mentioned the existence of a few devices which hold or held the potential to support navigation for people with visual impairment. In the interview the failure of some devices to catch on were discussed, however besides the failed Bose Frames (Bose, 2021) and the Envision AI glasses (Envision, 2021), no specific mention was brought up. Especially with haptics utilized. With this information accumulated, some notable devices can be presented.

The ’Sunu Bracelet’: This bracelet, developed by Sunu Inc. is specifically developed for people with visual impairment. It utilizes a ultrasonic sensor, which is applied on the wrist, to detect obstacles and warns its user from impending collision through haptic signals. The device is similar in size and shape as smart watch and is available for 299 USD. The device is designed to empower user with visually impairment and can be used in combination with guide dogs and white canes. It can be connected to an App on which manages its settings (Sunu, 2021).

The ’WeWalk Smart Cane’: This device, developed by WeWalk limited, is designed as a white cane with a large handle which provides extra features. The device comes with a variety of features. Primarily the device uses an ultrasonic sensor to detect low hanging obstacles in the users path, which it communicates through vibration motors. Beyond that the device pairs with a smartphone and comes connected with a variety of features. The user can use a mixture of touch and voice commands to navigate between points and revives audio based feedback on his location and surroundings if he wishes too. The device is further equipped with more convince features. It currently sell for 599 USD (WeWalk, 2021).

The ’Wayband’ bracelet: This bracelet, currently under development by Wearworks, is a device designed to assist users, especially those with visual impairment, in point to point navigation. The device is connected to an App, which lets the user choose a location. The device then creates a ”virtual corridor” to the target and uses motion tracking and haptic feedback to track the user and warn him when he is about to leave the corridor. The estimated price for the device is 249 USD (Wearworks, 2021).

Beyond these devices, as previously stated, a larger amount of prototype devices for research purposes exist. These have been categorized and talked about within the literature review. The following two devices are especially noteworthy for this paper, as they strongly influenced the research results and thus specifically mentioned within this chapter.

The multi-actuator tactile Bracelet by Paneels et al. (2013): This device, uses an assembly of six vibration motors mounted on a watch like structure, which provide users with navigational information as well as the identity of objects such as stairs or lifts in front of them. This is achieved through a special code which utilizes the actuators in sequences to create dynamic patterns which provide the user with information. The users intuitive understanding of these codes has been taken into account during their creation.

The HaptiGo tactile west by Prasad et al. (2014): This device uses a total of 6 vibration motors on the back to help users navigate and avoid obstacles. The device utilizes points at the shoulder region, to simulate a tap on the shoulder and produce an intuitive turn reaction by the user to guide him or her.

2.2 Methodology

The knowledge which was acquired within this chapter was collected in three ways. An initial desk research and literature review, an interview an expert in the field, and a number of smaller interviews with people with visual impairment have been conducted. Each of these methods served a specific purpose to either gain new information connected to the overall topic or specific research questions or to verify such information.

2.2.1 Desk research and literature review

For this part a number of 30 articles were retrieved from Scopus. These articles mostly contained information about the build, design and tests of different haptic navigation devices, as well as taxonomies of haptic devices and some design criteria for haptic devices. 10 of these articles were reviewed in greater detail with the use of a literature matrix to develop a literature review. The review mostly focused on three goals. To generate a form of taxonomy for these devices and to investigate each category, to understand the success of different types of devices, and to find factors which contribute to the intuitive understanding of transmitted information. These goals map to the sub-research questions 4, 1, and 2 respectively. The overall, less in depth research was further used to address research question 5.

2.2.2 Interviews

For the expert interview a catalogue of questions was created for the entire project. These were then initially addressed in an online interview with Timon van Hasselt an advisor for accessibility at Visio and an expert in the field of inclusive design for people with visual impairment. The Interview served as a first introduction into the area of design for visual impairment and helped to provide an understanding of our target group and their needs. Questions focused on more general topics initially and then narrowed down to each individual topic. The questions, which concerned this graduation project were mostly connected to sub-research question 2 and tried to gather information on how people with visual impairment use and feel about navigation aids.

Additionally, three interviews with people with visual impairment were conducted. The interviewees ranged from 25 to 65 and with varying stages of impairment. Questions in this case focused on the daily lives of people with visual impairment, the aids they use in their errands, problems in navigation which they face and how they perceive the world around them and certain user criteria which were found. In some cases they were also asked on their opinion on scenarios we made for our use case.

For both interviews the outline can be seen in Appendix A.

2.3 Literature review summary

Despite this apparent lack of successful haptic devices for visually impaired, a plethora of such devices were discovered within academic research papers and conferences. These include a large variety of devices with very different purposes and levels of development. The biggest distinction between each device was found to be the code, which were fairly unique every time. In order to structure the different solution it was first attempted to develop a taxonomy. Then, the resulting categories were analysed, the results of the devices compared and finally factors which contributed to intuition determined.

2.3.1 Taxonomy

The Taxonomy which was used to distinguish devices has been mostly based on a paper by Pacchierotti et al. (2017). They established a general taxonomy of haptic wearables by suggesting three major categories: (a) The type of tactile interaction; (b) Mechanical Properties; (c) Area of Interest. Additionally, many other reviewed papers also included a state of the art, which seemed to apply certain categories to structure and differentiate between solution approaches. Although not specifically mentioned, they did resemble the categories found in Pacchierotti et al. (2017). With this in mind the viability of each category was assessed. It was found that the most viable approach would be to use an extended version of (c) as a main mean of differentiation, while categories of (b) would be used to investigate results within each subsection of (c).

(a) contained the working principles of the interaction such as vibration, contact area modulation and proprioception. This category was not found much within other papers and was thus not deemed useful. While it has been used sometimes in addition to other categorizations such as in Jia et al. (2016) it did not seem to be as practical for the categorization of haptic navigation devices in comparison to just haptic wearables. This was also supported by Pacchierotti et al. (2017) which stated that haptic navigation devices usually relied on vibration motors. Thus, using (a) as a main category would have resulted in every device being within the same subcategory only and would not be viable. Within the reviewed papers, only Alayon et al. (2020) and Jia et al. (2016) have shown to use different actuators to convey information.

(b) contained the mechanical characteristics, such as Degrees of Freedom, Resolution or Bandwidth. This category did also find only little attention in the research, which has been reviewed for the literature review concerning the categorization. However, it most commonly appeared during many of the testing procedures within the reviewed papers as the influence of these categories or changes in these characteristics were investigated. Such is specifically the case with Alayon et al. (2020), Kessler et al. (2017) and Jia et al. (2016). Beyond that, the performance of devices was most commonly evaluated in how efficient certain characteristics of (b) influenced the perception of the instructions. Therefore, this category was most viable to analyse the performance and characteristics of devices within a subgroup, but was too inconsistent as a category for differentiation, as the many parameters were volatile within the devices and subject of investigation.

Further this category was adjusted to fit this paper. It contained a number of subcategories which were not relevant to this use case of haptic feedback, such as degrees of freedom and workspace. For the sake of this paper only bandwidth, which in the context manifested mostly in form of frequency (The rate it which information can be transmitted), resolution (number of actuators) and intensity (peak force) were considered.

Lastly, since the resolution used for each device was the only consistently available information it was used to structure approaches within each subcategory.

(c) contained different body regions on which the tactile feedback could be applied. This category seemed to be the most common one. A number of other papers such as Paneels et al. (2013), Prasad et al. (2014) and Jia et al. (2016) applied this form of differentiation. Prasad et al. (2014) and Pielot et al. (2011) further expanded these category to differentiate between wearable devices and handheld devices. This category seemed to be the most viable to differentiate between approaches, as the body area of application stayed constant for each of the reviewed papers. This approach was also the most rigid one, as apart from Jia et al. (2016) no reviewed paper used systems that targeted more then one area of the human body to convey information.

In accordance to the discussed categories, the categorization, which will be used for this paper to create a taxonomy was chosen as follows: All devices will be distinguished according to their area of application. These areas/ subcategories are: 1. Finger, Hand and Wrist; 2. Arms and Legs; 3. Back and Torso; 4. Abdominal region

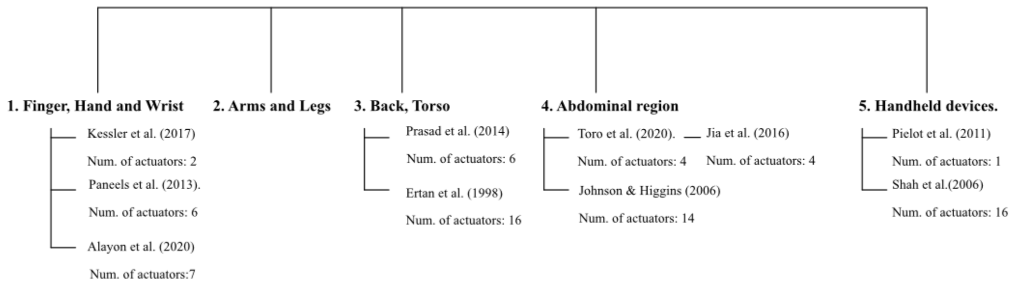


Figure 2.1: Overview

and 5. Handheld devices. Within each category devices will be sorted according to their resolution and analysed according to their bandwidth/frequency, resolution and intensity.

As was described the body location proved to be the most suitable category to reliably distinguish between devices, while the technical characteristics were the most important factors evaluated within the tests and thus subject to change.

With this information established and the devices analysed within the context of the literature review were distributed as can be seen in figure 2.1. Further it was now possible to gain some first insights into the distribution of devices along the categories within the taxonomy, to observe trends within the reviewed research. Predominantly it was discovered that different code types were being used in different regions of the body.

First, when it came to the distribution of devices within the literature reviewed for the Literature review, it was found that within the small sample size a relatively even distribution was discovered. Only Arms and Legs were not targeted by any of the reviewed devices, while the hand and abdominal region were the most popular. Many of the reviewed papers each take very unique approaches to their devices and thus a direct comparison was hardly possible. Besides varying in the number of tactors applied to the body, they each use very different approaches to which information is being transmitted and which code is being used. However, some similarities can be discovered within each category.

The devices belonging to category 1, the hand region, usually are very heavily based on more complex, indirect codes. Approaches are either a number of tactors arranged in close proximity to each other, which are combined into various signals (Alayon et al., 2020) (Paneels et al., 2013) or only two tactors representing left and right which are combined into with various frequency based codes to provide more detailed information (Kessler et al., 2017).

On the other hand, device centred around the abdominal region are using very simple and direct codes, with the position of the tactors indicating the direction. This can be seen with there being either a combination of 4 motors used to indicate the four sides around the user (Jia et al., 2016) (Toro et al., 2020) or a larger number of 14 to give a more detailed information. More detailed information is given not through code, but through resolution(Johnson & Higgins, 2006).

The same pattern can be seen for category 3, the back and torso region. Although, the information provided with these systems is slightly more indirect than in the abdominal region, they mostly rely on intuitive codes, like a tip on the shoulder pulling you back (Prasad et al., 2014) or a number of swipes through a 4 by 4 array (Ertan et al., 1998).

Lastly, for handheld devices, the two reviewed papers seem to rely on two very different approaches. While Pielot et al. (2011) use a smartphone with a single vibration motor to give straight forward directional information upon active use (pointing the smartphones in directions), the ’Ru-Netra’ system (Shah et al., 2006) relies on a semi complex code to guide users around obstacles.

2.3.2 Determining factors for successful communication

As was previously stated, the biggest difference between each reviewed device was the code in use. The codes could mostly be distinguished according to two code categories, direct, directional codes and complex codes. They were analysed to determine factors important for the successful transmission of navigational devices through haptics. In general most tests yielded successful results. The success of a device has been shown to mostly depend on the code used. Two factors seemed to be important for successful communication. First, more complex codes benefited from a lower frequency to transport their information, while second, more direct approaches mostly profited from higher resolutions. Further, using dynamic codes generally yielded positive results.

Since many of the reviewed devices were very different from each other they each were validated with very different testing procedures. Yet, in general most of the devices reported high success rates for accuracy, while some such as Prasad et al. (2014) determined, that the results were inconclusive when compared with other methods, but showed a lower cognitive strain on users.

It was found, that higher resolutions produced better results Alayon et al. (2020). This holds especially true for devices which apply more direct codes such as around the abdominal region or on the back, as Jia et al. (2016) proved. However, it was also proven with Kessler et al. (2017) that a number as low as two actuators can yield good results with the right code, showing that many solutions are dependent on the nature of their code, rather than just the resolution.

For more complex codes specifically, the frequency at which the information was transmitted played an important role. Not only did it influence the meaning in of the message in some cases (Prasad et al., 2014), but also how well the message was understood. Although dependent on the used code, slower and less complex messages were received better (Paneels et al., 2013) and also introduced less strain on the user (Prasad et al., 2014).

It was also shown that dynamic codes are better received as static codes, especially for more complex codes such as the one mentioned in Paneels et al. (2013). Successful use of dynamic codes can also be seen with Kessler et al. (2017) and even for more direct code approaches, such as the ones of Ertan et al. (1998) and Prasad et al. (2014).

Relating to intensity not much influence was found. However it was noted by sources such as Prasad et al. (2014) that factors like the human form are important to consider as well, as some body shapes would receive the information less intense than others, leading to more clarity errors.

It was shown that frequency influenced the performance of subjects the most, influencing not only clarity but also the strain introduced to the user as the most iteration in the reviewed testing procedures was concerned with this (Kessler et al., 2017) (Paneels et al., 2013). Most codes were received well by the users indicating that when it came to understanding many approaches could lead to a successful communication. Even rather eccentric codes like Alayon et al. (2020) and Shah et al. (2006) had positive results after some training.

2.3.3 Determining factors for intuition

With the factors for successful communication determined, their influence on the intuition of haptic navigation systems was evaluated. However, not much information was provided in the reviewed papers about intuition. The only previously determined factor, which could be linked to intuition was the frequency, as the mental strain was found to have an impact on intuitive responses. Beyond that however, an indicator was found concerning intuition, which is the usage of intuitive and dynamic patterns.

In cases like the ones mentioned in Prasad et al. (2014), Paneels et al. (2013) and Pielot et al. (2011), it was found that increased mental strain worsens the performance of test subjects. It reduced walking speed and led to more hesitant or wrong decisions and therefore it could be assumed that factors which increase mental strain such as a higher frequency influenced the intuitive perception of a system. This was reinforced by the fact that the papers which reported this effect mostly attempted to use codes designed for intuition. Other factors did not seem to influence the intuitive performance of users.

Instead it was discovered, that dynamic patterns, as well as patterns which utilize intuitive body reactions, have an influence over the perceived intuition. This can be seen in the works of Ertan et al. (1998), Prasad et al. (2014) and Paneels et al. (2013). The usage of patterns which produce intuitive reactions, like tapping on a shoulder to turn you around (Prasad et al., 2014), or patterns which reflect the intended motion (Ertan et al., 1998) (Paneels et al., 2013) seemed to produce intuitive reactions of the user. This said however, other approaches, especially those using more direct codes such as Jia et al. (2016) did not show signs of not being intuitive to the user, despite not explicitly being mentioning intuition

2.4 Interview summary

To gain more insights into the lives of people with visual impairment, especially to learn more about their design requirements and current relationship to technological Aids an initial Interview with Timon van Hasselt, accessibility advisor at Visio was conducted. First, the interview focused on the current situation and relation of people with visual impairment and technological aids. According to van Hasselt (2021) people with visual impairment are very much in need of more support for navigation. However, most currently available solutions do not manage to satisfy. He noted that many devices are not only expensive and sometimes break easily but also are designed by people who do not use or require the devices. Device often burden users, distract them, overwhelm them with information or are not designed with detailed use cases in mind. However it was also mentioned that the addition of haptics is in general a positive development.

After this several parts of the interview narrowed down questions which concerned the individual topic areas of the project. Concerning this graduation project, questions focused on how people with visual impairment interact with devices. Timon van Hasselt was not able to provide much information on this regard. However he mentioned that from his experience many people with visual impairment are quite confident in dealing with and applying technology, even though they mostly rely on voice to interact with it. Further from his own experience he adds that aids that focus on the wrist are better than those who apply on the back. He also mentioned the desire of people with visual impairment to use technology which is not exclusive to them, and to rely on devices which are being employed by visually able users as well.

Concerning the other question areas not much information relevant to this specific graduation project was revealed. Information gained in these parts will only indirectly influence this paper, as they contribute to the choice of the specific use case.

The user interviews contributed much the third research questions, as well as giving some neutral context about the lives of the users. They showed that factors as wearability (weight, sweat production) but also factors such as price and reliability play a large role in their choice of weather to adapt a technological aid or not. Additionally, it was found that criteria such discrimination through the design of aids can also play a role, however the opinions on this varied greatly. Generally the inclusion of haptics as a way of communication was seen positively by the users, although their opinion on how to use it varied.

2.5 Research questions

With this information collected, as well as information gained from the interview, the sub-research questions can be answered.

2.5.1 What are relevant factors that contribute to the effectiveness of haptic communication?

As has been shown with the papers reviewed for the literature review, haptic information can be successfully transmitted through a large variety of codes, including direct codes and complex codes. These codes further seem to relate to different regions of the body. Therefore the location has to be determined according to the information that needs to be transmitted. Complex codes require a lower frequency to be understood correctly and to reduce mental strain, while direct codes profit the most from an increased number of actuators to increase the resolution of the device.

Direct codes were mostly found for devices within the abdominal region and used the position of the actuators to give the user directional information. These codes benefited the most of resolution to provide more specific information to the user. The number of actuators here ranged between 4 and 14 (Johnson & Higgins, 2006) (Jia et al., 2016).

Indirect codes mostly relied on tactile symbols to convey information to the user or alternatively on more complex interaction between differently spaced actuators to provide navigational information (Alayon et al., 2020) (Kessler et al., 2017). These tactile symbols could be either static or dynamic in nature, whereby the dynamic codes were usually better and more intuitively received by the user. The range of complex codes starts with directional information in binary (Alayon et al., 2020) and stretches to all kinds of sweeps and patterns to convey different information to the user (Ertan et al., 1998)(Pielot et al., 2011)(Prasad et al., 2014). Interestingly enough, these codes seemed to be similarly well received by users as were the more simple codes. Complex codes mostly seemed to profit from a low frequency as it was shown that this increased clarity and reduced mental strain.

Depending on the chosen code within this project. The information obtained here can be tested and applied.

2.5.2 What are relevant factors that contribute to the intuitiveness of haptic communication?

When it came to intuition specifically some answers were found in the literature review. Dynamic patterns indicating certain information seemed to contain a certain level of intuition. This holds especially true for designs which utilize intuitive body reactions to convey navigational information like Prasad et al. (2014). A conscious utilization of these factors will help with designing a successful haptic device. Beyond that a low frequency which reduces mental strain helped to produce more intuitive reactions. The information gained for this research question can be formulated as design criteria which will help with the development of the design.

Design criteria for intuition: Intuition should not be overlooked as a design criteria, as it contributes towards accessibility and helps to reduce mental strain on the user, which intern contribute to the overall goals of this project to enable people.

1. **Dynamic patterns:**

   While the research did not yield much information about the intuition of direct codes, for indirect codes dynamic patterns were much better received than static codes. Codes which do not only consist out of one signal, but incorporate several steps to convey information as dynamic figures were shown to perform better and more intuitive(Paneels & Roberts, 2010).

2. **Natural reactions:**

   In the design of Prasad et al. (2014) natural reactions of participants towards certain sensory inputs were utilized to navigate the users. This idea might hold great potential to convey intuitive information to the user especially when it comes to navigational guidance and definitely should influence the choice of code. Beyond that it could help to keep the number of actuators at a minimum by making some information very easy to understand.

3. **Intuitive associations:**

   In the design ofPaneels and Roberts (2010) participants helped to form the code language used in the design by, giving associative feedback to the researchers about the meaning of certain patterns. This changed some of the symbols used within their code to be more close to the intuitive response of the users and increased the performance of the device. Using this approach to develop the code used should prove to be rewarding.

2.5.3 What are criteria of usability for a haptic navigation device for people with visual impairment?

Throughout the interview conducted much important information was discovered when it comes to design for people with visual impairment. While the actual physical properties seem to play less of a role, as people with visual impairment seem to be quite capable of operating such devices, the impact of the device on the user played the biggest role. Factors, like how usable and affordable such a device would be, or how it would burden or brand the user were found to be much more important. These again can be formulated as design criteria which support the development of the design.

Design criteria for visual impairment Designing for visual impairment is very much dependent on the views of people with visual impairment on the subject. Throughout the expert interview a number of criteria became apparent, which should be considered for the design of a haptic navigation device. These criteria are pervasiveness, wearability and discriminatory design.

1. **Pervasiveness:**

   This criteria which gained importance is the pervasiveness of the system. It was learned, that the design should not be in the foreground of the users perception and the to the perception of people around the user. This is important for two reasons. First, the design should feel natural to the user and not distract the users from the real world. Utilizing a form of design which grabs too much attention of the user through attention grabbing, high tech features does not support the devices purpose of enabling the user. Connected to this, the second reason for creating a pervasive design is the look it creates of the user in the eyes of other people. Creating a device which is not ought to be a dedicated fashion statement, but which is very apparent to observers, might create an unintended perception of the user. The user should not forced to look like a cyborg when using the device.

2. **Wearability:**

   This criteria focuses on preventing to burden the user. It should be considered at all time that the design should eventually be used by a large amount of different people over long time spans. Therefore, the design should be comfortable to wear and not limit the freedom of movement of the body through weight or shape. While the device would probably require a tight fit for the actuation to work properly (Prasad et al., 2014) it should not imprint itself on the users body or create areas of pressure, heat or unairiated areas which cause uncomfortable amounts of sweat. The design should be something that the user wants to wear and not something he or she is dreading to use. This is especially important for users with visual impairment, as they are already packed with navigation aids and do not have the capacity or the want to be further obstructed with ’aids’.

3. **Discriminatory design:**

   This criteria has been brought to attention through the interview as well as information material provided by material provided by the reflections course of the graduation project. According to Wittkower (2018) There are a number of designs which in their nature or use imprint discriminatory micro aggressions on the user. While this subject itself might be widely debated, it is hard to deny that certain designs convey a certain expectation towards its user in what is considered ’normal’ or ’abnormal’. Throughout the interview it was brought to our attention that people with visual impairment prefer to use technology which is not exclusive to their user group. The usage of devices only available to people with visual impairment might influence their perception of themselves negatively and brand them towards observers as ’abnormal’ for using a device which is not ’normally’ used. The design should avoid these discriminatory effects by utilizing shapes and form factors which are not exclusive for people with visual impairment.

Lastly, even thought not specifically found with research, the design should use a number of clear and unambiguous forms to ensure relatively error free operation by haptic information alone. A user should be able to distinguish orientation and important elements of the design easily to ensure the correct application.

2.5.4 Which forms of haptic stimulation are suitable for encoding information ?

It has been found within literature such as Pacchierotti et al. (2017), that there is a large range of possible haptic actuation principles and body locations which can used to convey information. These actuation principles range from cutaneous forms of feedback like vibration, stroking of surface geometry to kine static solutions which utilize different movements of the skin or body parts to convey information.

However, for navigational purposes only vibration is commonly employed. There was not much variety. Some papers such as Jia et al. (2016) or Alayon et al. (2020) used temperature or solenoids respectively instead of vibration motors, however besides that no other concepts were found to be used for navigational purposes.

Concerning body regions, The hand and wrist, as well as the belt area were the most popular, while there were no devices reviewed which utilized the arms or legs. The most distinguishable feature for haptic navigation besides the body location was the code, as even devices designed for the same purpose or the same body region used different codes to convey their information. As previously mentioned, these types of codes where simple, direct codes and complex indirect codes.

The information gained for this research question can support design decisions, especially the choice of the code and the actuation principle.

2.5.5 What are the qualities of different forms of haptic stimulation?

Not much information of the different qualities of actuation principles concerning navigational information was found. This lack of information can be attributed to overwhelming use of vibration motors over other actuation principles. No specific information about why this is the case was found. The results of Jia et al. (2016) indicate that temperature as an additional form of actuation showed a lower rate of successful communication with users in tests. Beyond that a number of possible factors can be compared to understand advantages a vibration motor might have. These include price, availability, flexibility, size and weight. While using other forms of haptic actuation over vibration is possible, as was shown by some papers (Alayon et al., 2020) (Jia et al., 2016) it would need to be clearly justified with design criteria. They would need to prove that in the specific situation they are better suited for the task, than vibration motors. Their increase in weight, volume and price they would bring to the table would need to be justified. This will be further discussed within the specification chapter.

2.6 Conclusion

To conclude the research, it was possible to follow each avenue defined by sub-research questions to learn about the field of wearable haptic navigation devices and to device criteria essential for the design and development of user centred, intuitive design. The field of wearable haptic navigation devices is wide, yet under-developed when it comes to not only successful but also usable designs. Therefore, some of the discussed information might require a larger amount of study to accurately determine their viability. However, the level of information is definitely able to to provide enough information to serve as a source of reliable thought input.

Chapter 3

Methodology

In this chapter the methodology for this Graduation project will be established and described.

Due to the circumstance of the project, of being a graduation project in Creative Technology, the development process itself forms an important aspect of this report. The iterative Creative Technology development process held significant influence over the way problems were approached and how often certain phases of the product development were revisited over the course of the project, as well as the time spend on each phase and iteration. Therefore, a quick introduction into this specific development process will be provided.

3.1 The Creative Technology development process

According to Mader and Eggink (2014), the creative Technology development process consists out of four interconnected phases, which aim to combine design practices with engineering practices to create user centred technology. These four interconnected phases are Ideation, Specification, Realisation and Evaluation and are usually being revisited several times throughout the development process. On a lower level, this process is based on two design practices, divergent and convergent paths and spiral iterations.

Divergence and Convergence: This concept entails that during a development process diverging and converging phases are used to ’open up and define’(Mader & Eggink, 2014) the design space by creating a number of different solutions for a given problem initially, to explore more avenues of possible solutions, which are then later within the design process narrowed down to one solution, according to their results and specific properties.

Spiral Iterations: This concept is based upon the idea, that each step within the development process, should happen, as needed, in repeating cycles building on one another. Developers can use this to generate insights through the testing and analysis of different prototypes, and then to return to another ideation or specification step with the newly gained knowledge to develop another generation of prototype devices.

As mentioned, the process includes four phases. While they are commonly employed in the described order, they each are interconnected in the way, that developers have the freedom to repeat or return to any number of previous phases in larger iterations, according to their needs. The phases can be explained as follows:

Ideation: This phase aims to generate a plethora of ideas and concepts which can be pursued during later phases of the development. For this end, a number of techniques and steps can be used. These can include, research and interviews, the creation of use cases, user needs and design criteria, scenarios, and creative thinking methods as well as brainstorming techniques. Depending on the situation of the project these techniques can be applied and chained together to create ideas which then can be addressed in the next phase of development.

Specification: Following the Iteration, developers can enter a specification phase. Similarly to the previous phase, a number of techniques are available to be combined and applied in several steps with the goal to transform the ideas from the first phase into a concrete concept which can be build and applied. In this phase, developers can specify the user experience through user centred design methods, such as storyboards, but also design and refine the technical aspects of a given idea, in terms of materials, components and systems used. This can be amplified with simple prototypes.

Realisation: The defined concept of the Specification phase can then be applied to create a specific prototype, which can undergo proper user testing. This process is commonly more straight forward than the previous phases. During this phase some specifications may change, yet the goal is to produce a usable device for the following evaluation phase, by decomposing the device into components which can be realized step by step.

Evaluation: This final phase contains user or function tests of the prototypes resulting from previous steps. The specific results of each test can then be used to evaluate the state of the project and future steps can be identified on the basis of these results.

3.2 The application of the Creative Technology Process for this project

This concept of the creative technology development process has been adapted for this project in three major iterations. An overview for this can be found in figure 3.1. Each iteration is focused on different aspects of the project. These will be described at the beginning of each following section.

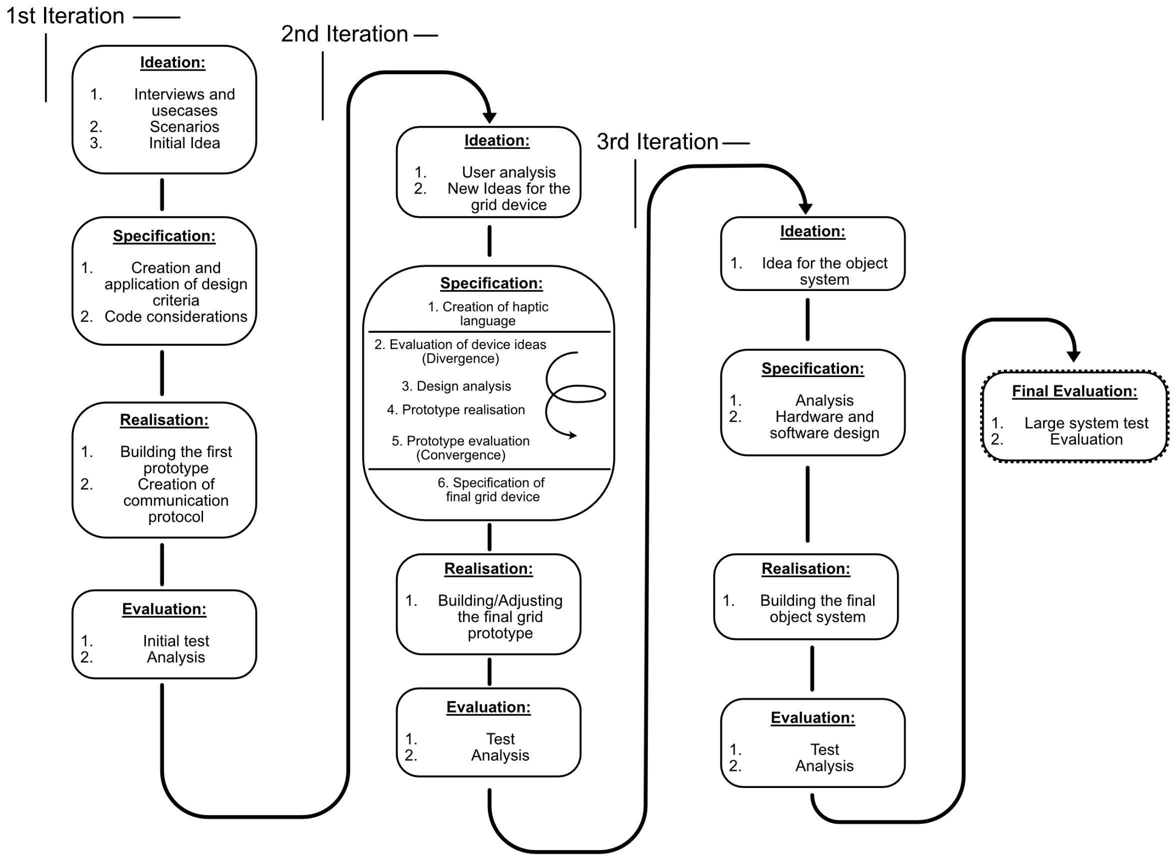


Figure 3.1: Overview Iterations

Chapter 4

1st Iteration

This section describes the first of three major iterations which form the development process for this bachelor project. Within this iteration, all four phases of development have been employed.

4.1 Goal

This initial major Iteration served two goals. First, to get an initial estimate of the challenge imposed by the project. Second, to gain an understanding of specific problems of the matter and of techniques which would need to be applied to solve these problems. For this end, an attempt was made to develop a very simple initial idea and prototype, upon which could be iterated on. Following simplicity, the process towards the final product of this iteration was a rather straight forward one.

4.2 Ideation

The first step within this iteration was the ideation phase. This phase happened for the most part in cooperation with the other students working on the project.

4.2.1 Interviews

The first step after the initial desk research was to gain more insight into the client group, as the collected desk research appeared to be limited in this aspect. To achieve this an initial expert interview with the Timo van Hasselt, accessibility advisor at Visio was conducted, as well as three interviews with clients with some form of visual impairment. This step has been described in more detail in the previous chapters, as far as it concerned the answering of research questions. Furthermore however, it served the purpose of gaining a direct understanding of the potential user of our device. It is imperative, that when development happens for a specific client, developers become familiar with the client themselves in order to facilitate a successful adaptation of technology for the required use. Therefore, besides asking clients questions which relate to specific research questions, they were also invited to talk in a less structured manner about their day to day lives and struggles, their perception of the world and of devices which they already use for assistance.

With this information, an overview over the most common problems, which people with visual impairment deal with, and which could be addressed with the knowledge we gained from our interviews. These problems are:

Missing obstacles due to limited awareness: This problem describes the circumstance, that people with visual impairment often lack awareness of obstacles around them, such as stairs, doors, ditches and edges. As a result, people with visual impairment often get lost or manoeuvrer themselves in difficult and dangerous situations. This is due to the very limited detection range of the cane, which only covers around 1 meter in front of the person. In some cases objects even slip the detection by the cane and become a dangerous problem for people with visual impairment, capable of causing significant injury and insecurities.

Loosing and finding objects: This was found to be another rather common issue for people with visual impairment. As they cant rely on sight to handle objects, they have to carefully organize and memorize the positions of their belongings and utensils. Accidents, such as misplacing or dropping objects can thus very easily cause frustrating situations, in which objects ’disappear’ from the persons horizon and can only be found through time intensive and sometimes dangerous search operations.

Wide open or new areas: Many people with visual impairment seem to have difficulties when it comes to new or wide open areas. In both cases, the lack of orientation points and the inability to rely on experience to overcome these situations, become a severe limitation for the independent mobility of people with visual impairment.

Unreliable supports and equipment: While this problem is less of a direct navigational problem, it seems to be rather common when it comes to technical supporting devices or other helps such as the guidance dog, and thus also affects mobility and navigational capabilities. Many devices, which are used by people with visual impairment, are limited to very specific situations and boundary conditions, which make them unreliable in the eyes of some of our interview partners. For example we learned, that guidance dogs, have to be trained and kept in very specific conditions in order for them to continuously fulfil their purpose of guiding people with visual impairment along only very limited routes, and thus are not always a viable and reliable assistance in navigation.

4.2.2 Use cases

As a next step, we put these problems within specific use cases, adding a goal to solve the problem and creating scenarios for the problem, of which a decision could be made what problem to pursue.

Use case 1: Create awareness of the surroundings: This use case is based upon the problem of missing obstacles due to a limited awareness of people with visual impairment of their surroundings but also relates to the problem with new areas. The goal for this use case would be to develop a device which would be capable of increasing the awareness of people with visual impairment of their surroundings, by providing them information beyond the range of the cane. This would serve to empower people with visual impairment to make more informed decisions about where to navigate within a given environment and could serve as a support for the ”last five meters” after using a point to point navigation device to reach a certain shop or place. A concept like this could be capable of restoring confidence in users again, as it could increase their understanding of the environment. Scenarios could be, to find a street crossing, walking along twisted lanes within a park and finding your way within a mall.

Use case 2: Create an anchor point system to explore unknown environments: This use case is centred on the problem of wide open and unknown areas. The goal for this use case would be to make it safe for users to explore these kind of problematic areas, by giving them the security to find their way back to known points. A device would track the users movement and could offer the functionality of saving specific locations at which the user could return to in case he/she would get lost. With such a device, users could safely explore difficult areas in form of ’expeditions’ and enable them to move more freely again. Scenarios for this use case would be, to explore a flea market or to return to a bus station after a trip to the city Center.

Use case 3: Create a supporting device for keeping track of objects and finding lost objects: This use case is centred around the problem of loosing and finding objects. The goal would be to create a system which can observe and keep track of objects, which are used by people with visual impairment in their day to day business. In case an object drops or is getting lost, the user can then tell the device to guide him to the current location of the object according to when it was last detected by the device. It could also warn the user for danger, such as when the user searches for keys dropped on the street. Such a device would have the potential to increase the quality of living of a user as it could ease frustrating and time intensive search operations. Scenarios for this are, the user loosing their purse on the street or the user trying to find a glass of milk he placed on the table earlier.

With these use cases at hand we decided to pursue the first one for several reasons. First, it seemed to be the most urgent one according to heuristic estimates from the interviews, and also addresses an issue which has probably the most direct influence on a persons well being. It was also found, that the respective departments would be equally challenged, which should distribute work between team members more equally. Lastly it would be the most relevant use case to enable navigation for people with visual impairment.

4.2.3 Scenarios

After making this choice the team, focused on developing the scenarios for this use case in more detailed. Following are the five scenarios, which were developed.

Scenario 1: This scenario (Figure 4.1a) sees the user in a city environment, in which he/she needs to cross the street to reach his/her goal. First, the crossing needs to be identified, then a safe path across the street needs to be taken to complete the scenario successfully. During this scenario the user should not walk on the street by accident and should also not collide with other obstacles.

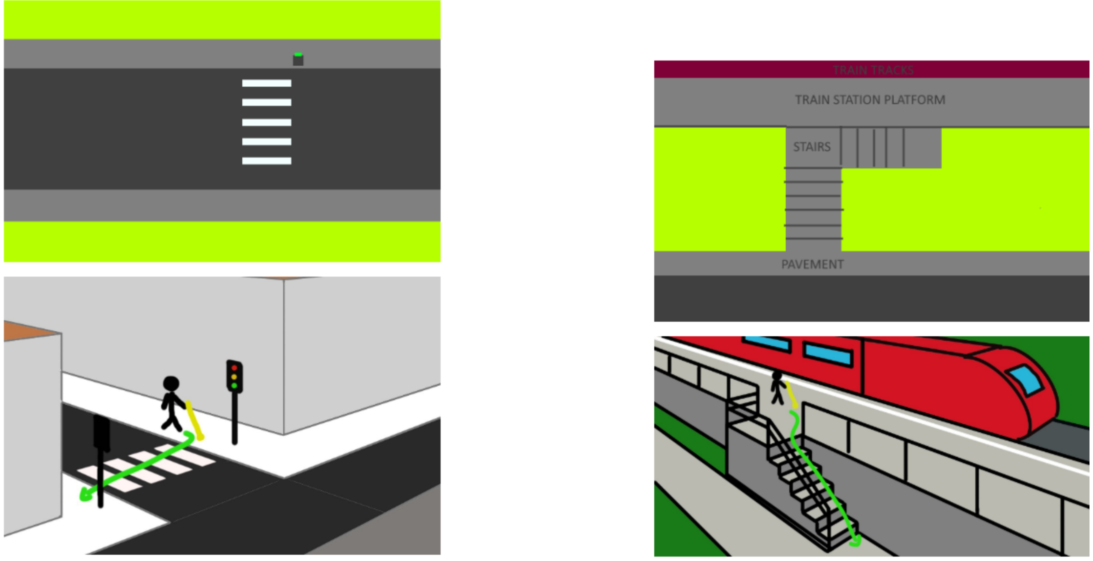
Scenario 2: This scenario (Figure 4.1b) sees the user on a train platform after the user left the train. He/She now needs to find the way towards the stairs, without colliding with fences or other objects and without accidentally falling onto the rails.

Scenario 3: This scenario (Figure 4.1c) sees the user walking along a straight street on the pavement. As there are no physical points of orientation available, which would keep the user from walking onto the street or slipping into the ditch on the other side, the user needs to rely on the device to walk straight.

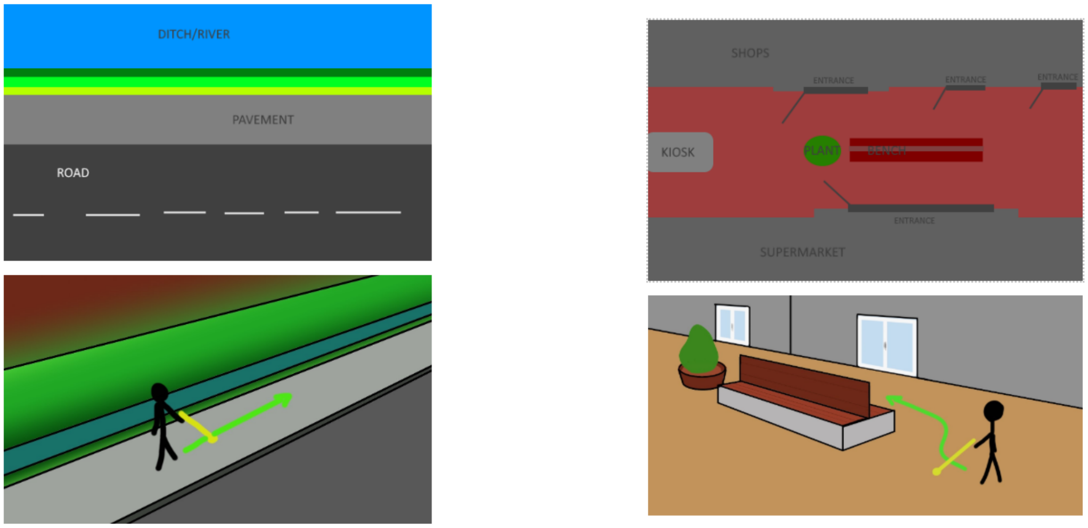
Scenario 4: This scenario (Figure 4.1d) envisions the user within a mall. He/She needs to find a shop entrance along the sides of the mall, while avoiding signs, benches and other obstacles.

Scenario 5: This scenario (Figure 4.1e) follows the user through a city park, full of uneven and twisted paths. The device should provide the user with enough information to stay on the way an to not walk onto the grass. Also, benches and bodies of water should be avoided.

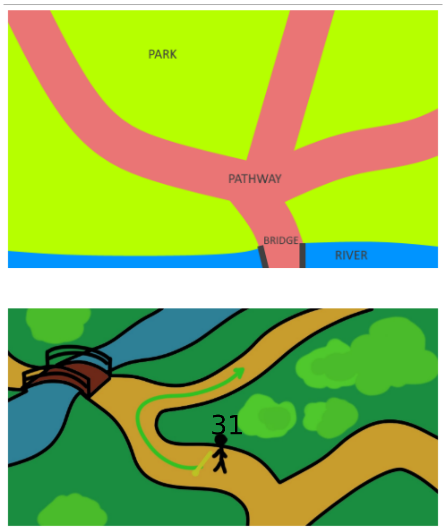
Final choice: Due to limitations and time constraints within the project, it would be necessary to limit the primary scenarios, which would be addressed, to three. After careful consideration and consultation with some of our clients, the focus was put on Scenarios 1,2 and 4. The team decided that these scenarios would be the most common and pressing ones, amongst the five and that they would further provide the most insightful testing results.



(a) Scenario 1 (b) Scenario 2



(c) Scenario 3 (d) Scenario 4



(e) Scenario 5

Figure 4.1: Scenarios

4.2.4 Idea

Some simple brainstorming was done to create an idea for a device which could satisfy the requirements determined in the goal for the use case, and which should be an axis of orientation for each separate bachelor project. This resulted in the following concept.

The device would be inspired by radar systems and as such would distinguish the area in front of the user into discrete cells, according to a grid like system, which would be scanned and then communicated to the user in defined consecutive sets (cell-by-cell, row-by-row or column-by-column).

Each cell could hold informations on whether this area would be passable or not, and whether special objects would be present. Occupation of a cell could be further distinguished, on whether the ground is even, lower or higher, completely obstructed or unknown. Special objects could be doors, stairs, streets, street crossings and more.

The user would learn about this through a grid of haptic motors, applied to the users body, which could communicate cell information through patterns and intensity. Special objects, which require a more complex system, could be communicated trough a tacton system, in which an arrangement of actuators can be can be activated in different orders to create a unique combination symbolizing an object.

In combination, these systems could create an impression of the environment in front of the user, being able to communicate where, how far, and what type of obstacle there is in front of the user. This system could either work continuously or at the will of the user and the level of detail could be adjustable on the go, by for example disable the tacton system and relying on the grid alone.

A visualisation of the idea can be seen in figure 4.2. The blue dot is the position of user. Green shows the position of a special objects such as a door, black the position of obstacles. Red cells are occupied.

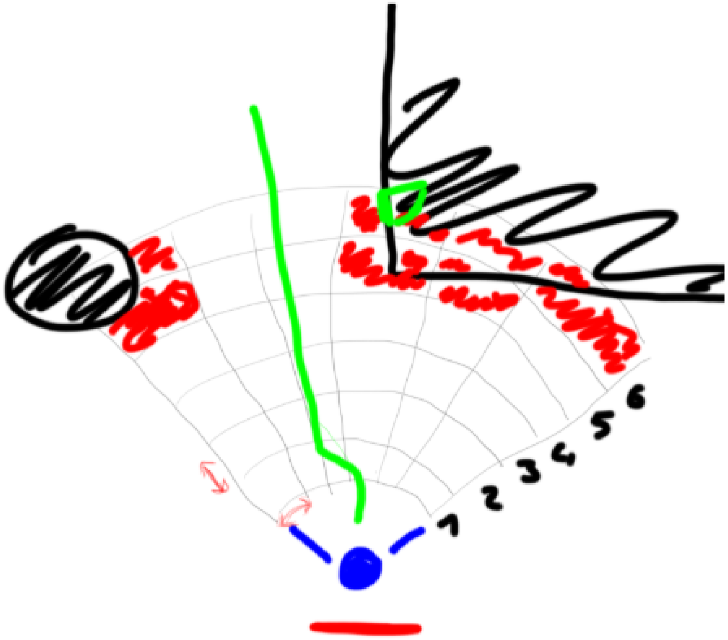


Figure 4.2: Concept

Lastly, since the device should work in as an addition to the cane an not as a replacement, the area which would be covered by the cane would not be covered by the device. The system would begin scanning in a cone radius beyond one meter up to 5 meters.

4.3 Specification

The goal of this section is show the process of transitioning from the idea to the first realization. As the first iteration was meant to be rather straight forward, the specification for this Iteration was kept simple. However, still some considerations were made to transform the initial idea in to a defined concept.

4.3.1 Goal for this specification

As the goal for the iteration was to create a simple proof of concept to gain experience and discover possible avenues for the device, a simple, but flexible, version of the idea should be build. First of all, this meant omitting the object tacton system for this iteration and include it later in the project again. Second, the device should therefore focus on the grid only and on question concerning the feasibility of the concept as well as the different design dimensions of the concept, such as the resolution, and width and depth dimensions of the system. The prototype should be build to test different version of these dimensions. To further simplify this concept, the grid should only distinguish between free and occupied cells. Differences in height as well as unknown values should not be counted.

4.3.2 Design Criteria for haptic wearables

With the background research collected, design criteria for a haptic device were created, which aim to guide the development of the concept, by influencing the decision making process for certain design dimensions. Therefore, these are similar to the criteria for intuition and design for visual impairment, which have been established as answers to research questions beforehand.

Body location: This criteria asks the fundamental question of where on the human body the actuators should be placed. Not only have different body parts different receptor densities which makes them more or less ideal for certain designs, but also afore mentioned desk research has shown, that different body regions can be associated with different codes. This entails that to choose the ideal body location, the type of information, which is supposed to be transmitted has to be known. Beyond that, the physical dimensions of the eventual design are also influencing the ability of applying the device to different body regions as they might have negative consequences on the usability when put at the wrong locations.

Type of actuators: The choice of the actuation type is also an essential criteria. Fundamentally, there are little limitations which are connected to the type of actuator used, besides the type of code. However, it seems that vibration motors are the most viable choice. They are not only lighter, cheaper, smaller, easily available and more flexible than most other types of actuators, but also showed to be successful in the covered research and better understood by the user than temperature actuation (Jia et al., 2016). This being said, it would be interesting to test different forms of haptic actuators, like form example pressure actuators.

Number of actuators: Once, code, body location and actuator type are chosen, this criteria has to be considered. It mostly follows the afore mentioned criteria, however it also does have an influence over the chosen language. With only a certain number of actuators possible per body part, before signals become unrecognizable, the used language is dependant on the possible number of actuators (the maximally possible resolution). This number is also influenced by the chosen resolution, which intern depends on how fast the system should be and how much humans can understand. It can be assumed that the resolution should therefore be rather low and thus should the language work with as little actuators as possible.

Affordability: As price considerations showed to be an important factor for end users and the adaption of a technology, it is important to keep cost considerations in mind with the design. Relying on actuators and materials which are generally considered affordable might not be possible in the entirety of the project, especially for the prototype, however it can be avoided to base the design around costly concepts, such that it its core design is easily affordable.

Sturdiness: Another important factor is the sturdiness of the design elements. It has been shown in the interview, that in order to justify the buy of such a technological navigation support, the device has to survive and operate reliably over a long period of design. Therefore, the design should avoid fragile or vulnerable elements and should also account for other external factors, such as strain, heat or rain. While again, this might not be a primary concern for the prototype, keeping this criteria in mind during the design phase helps to avoid design flaws.

Physical dimensions: The physical dimensions of design elements have the be kept in mind at all times. These include weight and volume. As these factors influence a number of other criteria keeping them both at a minimum is important. Decisions for design elements should keep the influence of both of theses factors on the degrees of freedom and physical strain on certain body locations as well as on the wearability in mind.

4.3.3 Application of design criteria for the first Iteration

The design for this first prototype should remain simple and focused on being easily able to change the actuator layout in different dimensions to test for specific criteria. For the body location, the back was chosen, as it fits the code idea of being a rather direct code and the back has enough space for different sizes of grids to be tested. The actuators should be around 2 to 3 centimetres apart according to Mancini et al. (2014) values for successive stimuli and Zeagler (2017). The actuators should be vibration motors, due to flexibility, availability, price, weight and energy consumption. To keep the prototype simple, only the minimally necessary amount of actuators should be chosen. For this prototype a number of 6 was considered acceptable. As for the wearable itself, a widely available, but comfortable and flexible garment should be chosen. Research showed, that softshell seems to be an appropriate material, as it is comfortable, stretchable and can be cut easily while maintaining consistency. This is also inline with the affordability criterium as all components so far are inexpensive. To ensure sturdiness, but also ideal contact with the user on top of his/her clothings, actuators should be put on the inside of the wearable in pockets, reducing the risk of faulty contact with the participant. Beyond that softshell garment can be considered a sturdy material. All of these decisions suffice the criteria for physical dimensions, as components are light weight and only of little volume.

4.3.4 Code considerations

As the prototype is meant to be flexible and adjustable in its dimensions, the code needs to be written in a way to be easily adjustable. Beyond that, it would be beneficial to create a sound code base, upon which further expansions of the project could run as will with only little changes. Therefore, the available output channels, as well as their layout should be easily adjustable in the code and the behaviour and nature of the code should be easily adjustable as well.

4.4 Realisation

With this being specified, a prototype can be realised, which should suffice the specified demands in hardware and in code.

This prototype can be, being located on the back of the user, a simple rectangular piece of clothing, with pockets in a grid in which actuators could be put. The dimensions of this, given that only six actuators should be used, can be 5 by 3 cells. This enables tests with small grids, such as 2 by 3, as well as one dimensional tests for up to 5 actuators in depth or width, depending on the orientation of the rectangle. Double sided tape could be used to easily apply the prototype to the back of users in different orientations. The input for the prototype would be provided by a simulation program in unity designed by Tim Yeung and should happen over a serial communication protocol which would also be used by the sensor later on in the project.

4.4.1 Choice of hardware

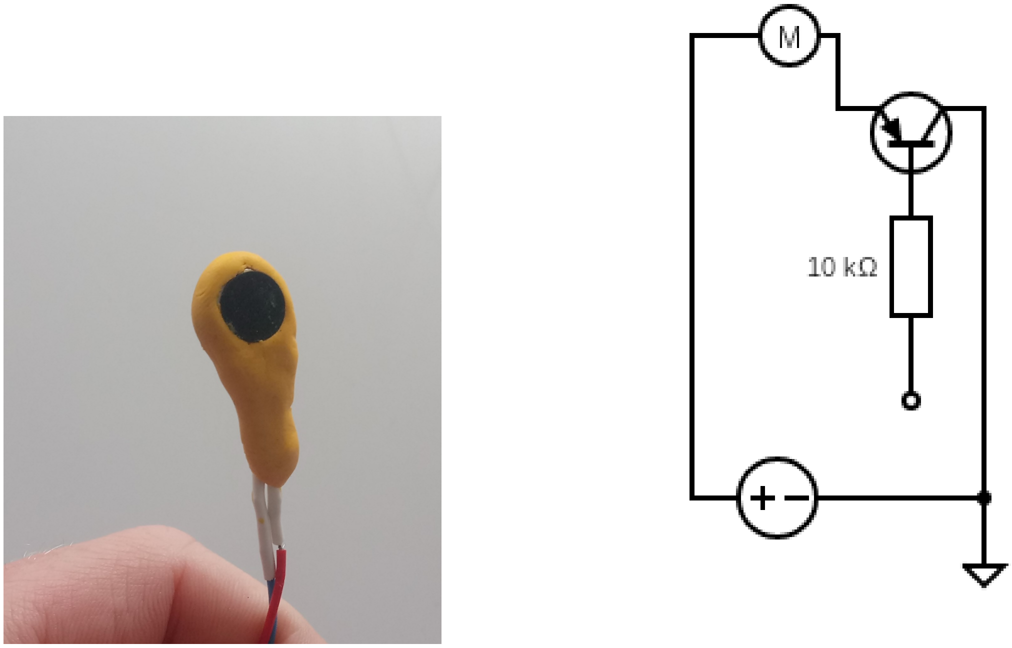
Garment: As has been mentioned with the specification, the choice of garment should be softshell, due to its flexibility, comfort, stretchability, sturdiness and wide availability. Softshell can be cut into any shape, without having to repair edges to prevent the cloth from dissolving. It can also comfortably adjust to different body shapes.

Vibration motors: The motors have been provided by the supervisor of the project. The chosen motors are coin vibration motors, which fit the best the specified requirements of physical dimensions and flexibility. They operate at around 3 volt and only require very little current. A PWM signal would be used to control the intensity of the vibrations

Microcontroller: A microcontroller is the most convenient choice for a hardware prototype. For this project the Adafruit HUZZAH32 - ESP32 Feather was chosen for the reason, that it is a very powerful and flexible microcontroller (Adafruit, 2021) . The controller can use serial communication via USB, which can be used to communicate with laptops or the sensor part for input. It also possess internet and Bluetooth capabilities, as well as built in battery management, in case the project would switch to wireless at a later stage. The ESP 32 microchip can provide a voltage of 3,3 Volt for hardware devices and a peak current of 250mA for external devices. This fits the hardware requirements of the vibration motors. Lastly the ESP 32 comes with a very compact form factor and 11 PWM output channels, which makes it easy to use for wearable haptic projects.

4.4.2 Building vibration motors

The first step towards the prototype was to assemble the vibration motors, by adding longer cables, the necessary electronic components and a connector to make it easy to plug the vibration motors into breadboards and PCB boards. Heatshrinks were used to cover up solder spots. The used circuit design can be seen in figure 4.3b. As a last step, to protect the vibration motor and its contacts from breaking, moldable ”Sugru” glue was used to cover the motor (Tesa, 2021). The motors were then tested and their current draw was measured to be 3 m Amp.



(a) Result

(b) Circuit

Figure 4.3: Vibration motor

4.4.3 Code base

To fit the specified requirements for the code, several code structure were considered. To achieve this, the idea was developed, that the code would segment and save individual vibrations as a form of base instructions, which could be attached and read by individual output channels at will, thus creating a small form of language of programmable instructions. Higher instructions, which would combine basic instructions should be possible as well, but implemented at later stages. This would make it possible to create a variety of different versions of prototype devices for this iteration, but also for the future, as instead of rewriting large portions of the code or changing functions, just the instruction set would need to be changed to test different languages. Basic instructions should contain a duration, an Intensity and the number of repetitions a signal should have.

Another feature, which was included in the code, was the autonomy of output channels. Instead of being reliant on a large loop to change the signal for a given channel, channels should work as separate objects capable of understanding basic instructions and to turn on and off without external needs, when assigned a basic instruction. This feature was meant to make the management of different outputs easier and more reliable.

Initially, for this purpose, an interrupt based system was planned, however further research showed, that the inability for interrupts to reschedule themselves made this plan unviable. Instead a more flexible task oriented program structure was chosen. This was enabled, by the use to the TaskScheduler libary for cooperative multitasking for Arduino by Arkhipenko (2021).

Within this structure, each major function, such as communication and understanding, as well as each operating output channel is modelled as a Task, with a main function attached, as well as pre and post functions, and a designated pointer to a struct, which would contain all necessary variables and, in case of the output channels the location of the basic instruction. In between tasks, the library offers the function to put the controller in a sleep mode to save energy.

Lastly a button task was implemented, which would tell the system to start requesting sets if the button was pressed, for as long as there are sets left. This was implement to not overwhelm the user with constant input.

This lead to the program structure, which can be seen in figure 4.4.

The code has been written in the C-based Arduino language.

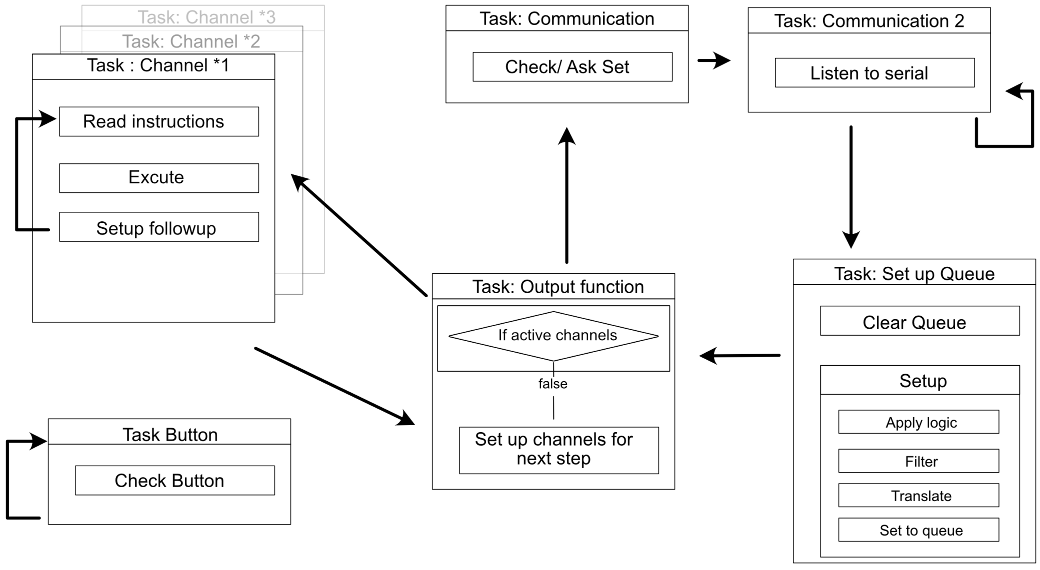


Figure 4.4: Code structure

4.4.4 Communication protocol

To ensure that the device would work smoothly with the other parts of the project a common communication protocol was designed. This should not be changed later on and thus was designed to be flexible enough to include all functionalities defined in the ideation step. Therefore, it includes a number of options for different cell values and the possibility to communicate special objects for each cell.

In figure 4.5 it can be seen, that the created communication protocol consists out of two steps. First, the wearable device would ask the sensing unit, for the input of a specific set, by sending the assigned capital letter to the input device. Such a set could be a row or a column within the grid, but could also be defined otherwise if needed. The input device would then answer the call with an array of characters, following the same pattern for every cell within the set. First, a header in form of a lower case letter will be sent to signify which cell will be sent next. This is followed by a cell value which can range from 0 to 4 to signal whether a cell is free (0), occupied (1), unknown (2), higher (3) or lower(4). After this, if there are special objects within that cell, a maximum of three objects can be appended, each consisting out of a three digit number from 000 to 999. The most essential objects like doors, streets and stairs were defined to occupy the space from 001 to 007.

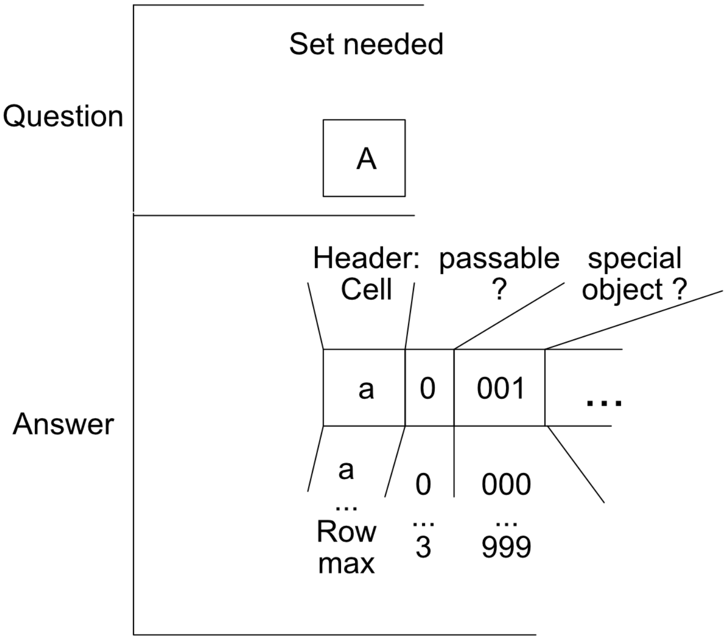


Figure 4.5: Communication protocol

4.4.5 Language and final prototype

Concerning the language requirements for the prototype, the information which needed to be transmitted consisted only of whether an element in a predefined cell is occupied or not. Therefore, two basic instructions were created which can be executed by output channels depending on the data. The first one is, a long one second buzz at maximum intensity if a cell is free. The second one is a one second long buzz consisting out of two consecutive shorter buzzes to signify, that a cell is occupied.

To find the right intensity values for the vibration a small test was conducted in which different intensity levels were compared to each other(Figure 4.6). It was found that high intensity values might be necessary to communicate information clearly. For this prototype the maximum value was chosen.

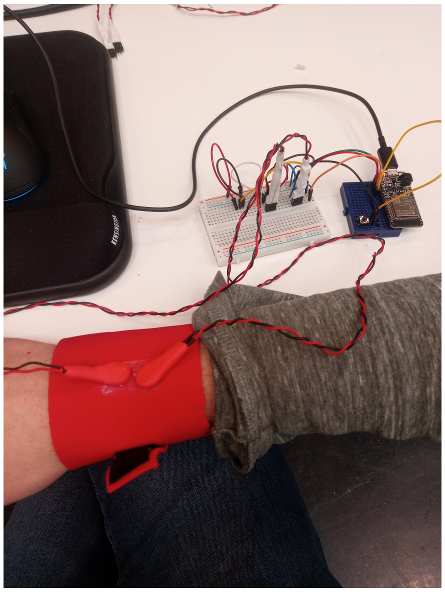


Figure 4.6: Intensity tests

This led to the final prototype for this iteration which can be seen in Figure 4.7. The pockets for the actuators where made using a plastic foil and a special textile glue.

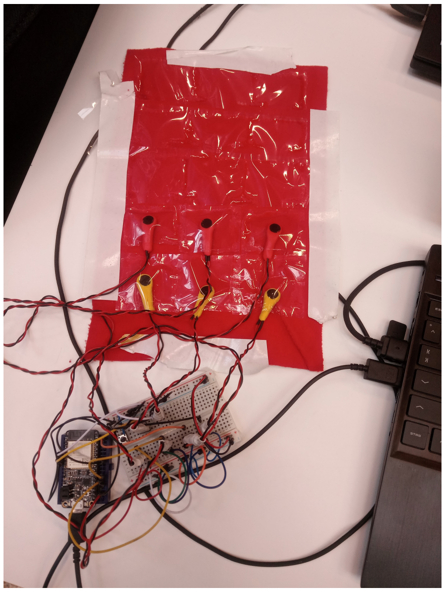


Figure 4.7: Prototype

4.5 Evaluation

To evaluate the performance of our idea, in terms of width and depth perception, to determine how the resolution should be, the following test setup was designed:

4.5.1 1st test:

Goal: Investigate differences in the (width) perception of space with different fields of view.

Two setups:

1. 3 Columns, 2 Rows (3 sets of 2)
2. 2 Columns, 2 Rows (2 sets of 2)

Both setups will be provided with the same input, of a virtual example scenario with 2 objects akin to boxes in front of the user. Both objects stand within the field of view. The output is rendered according to the hardware setup. The user will be seated on a chair and the prototype will be applied to the users back on top of the shirt. They can then turn their head around, which will be mimicked in the unity test program by one of the operators. The user can then ask for information and the button will be pressed by another operator, which will cause the prototype to print all sets once. This then can be repeated. The subject should investigate the space by listening to the device and afterwards draw the perceived position of the objects on a template. The test program was provided by the team member Tim Yeung.

4.5.2 2nd test:

Goal: Investigate the difference of depth resolution on the depth perception of the User .

Two Setups:

1. 1 Column with 4 motors (1 set of 4)
2. 1 Column with 5 motors (1 set of 5)

Both setups will be provided with the same input again showing two objects, one at the edge of the field of view and on between the edge and the user. The objects are this time on one line and the user does not need to turn their head. The input is rendered accordingly to the setup. The test setup is similar to the previous one. The subject knows, that the distance to the edge stays the same between prototypes. The subject is then asked to indicate the distance of the objects on a line.

4.5.3 3rd test:

Goal: Investigate the difference of row increment distances on the depth perception of the User

One Setup:

1. 1 Column with 5 motors (1 set of 5)

Test runs two times with the same scenario of an object standing 2 meters away from the user. Again, the objects are on one line. The user does not need to turn their head. For each test the scenario is rendered differently with .5 meters increment between rows and and 1 meter increments between rows. The test setup is similar to the previous one. The Subject knows the increment size. The subject is supposed to indicate the distance of the object on a line.

4.5.4 Test results

The test was conducted with a team member as a volunteer to try out the different configurations. The results can be found in Appendix B.

4.5.5 Analysis and conclusion

It has been shown that the basic concept seems to work, as the participant was able to tell differences between free space and objects. However the perceived precision showed to be problematic. As can be seen in the results for the first test, the user had significant problems to place the objects. It could be argued, that the prototype with higher resolution yielded minimally better results. On the other hand, the second test showed that while there were some misconceptions about the amount of objects in front of the user, the allocation of the objects was much more clear and closer to the intended setup. Even though the second variant yielded better results, the results of the first setup, apart from the missing object are more accurate. Similar findings were the result of the third test.

This showed that either complexity plays a significant role for haptic communication, more significant then expected from literature, or, additionally, that while depth perception is rather accurate, the perception of objects in angle in front of the user requires more accuracy.

Despite the inaccurate nature of the test, this shows that there seems to be a problem with the concept so far, which needs to be fixed in the next iteration.

Chapter 5

2nd Iteration

This chapter describes the second major iteration. Within this iteration all four phases have been followed through, as well as some iteration and testing of minor prototypes happening within the specification phase. Due to time limitations and hold ups, parts of the minor iteration within the specification had to be completed after the end of this iteration and had to be added retroactively. This also lead to some situations in which knowledge gained in the third iteration influenced some of the specification within this section.

5.1 Goal

The Goal of this iteration was to develop a working grid device with a working language. To test some possibilities of how an improved version of this could look like, divergent paths were taken to create and analyse different language solutions. In addition, more research into language and user centred design was done and taken into account. Originally the development of a language, was distributed between two students, however the second student dropped out of the project and thus the development of the language became entirely my obligation.

5.2 Ideation

The results of the last user test showed, that a number of improvements need to be made in this iteration, to produce a working prototype. For this reason, another ideation phase was initiated, which focused on identifying more useful user criteria and to generate new ideas on top of the old concept to make the device faster and more reliable.

5.2.1 User analysis

To ensure a user centred approach for the design of this device and its language human centred design techniques were applied to guide the development of this iteration.

PACA analysis First a PACA analysis was created, which analyses the way a user would interact with the technology and is centred around questions, which aim to unwrap user expectations and conditions, as well as environmental conditions, through a heuristic analysis. The detailed results can be found in Appendix C. The analysis for example reinforced, the urgency that users will not have much time to interact with the system, as they will use it while being mobile. With the time constraints haptic communication has, it becomes important to consider this criterium more. The analysis also raised awareness, that users do not only want to be informed, but also expect that the system will not overload their understanding and that the system will make them safe. As resolution problems were found in the previous iteration, the way forward might not be, to find a way to increase the resolution and speed it up, but rather to encode it in a more simple way with the effect of increasing the confidence of the users. Lastly, the system should also increase in clarity, as it will be used very commonly and frustration should be avoided.

Goal analysis As a next step a goal analysis was done. With this analysis, the aim was to understand the central design conflict of the device and searched to find a bias to influence other design decisions. The analysis and its result can be found in Appendix D. During this process, first the design goal of the project was dissected, to uncover a central conflict to the device. It was then attempted to map evidence from the previous test and research on a spectrum between the two concepts forming the central conflict to produce a certain bias towards one or the other. In the case of this project, the central design goal was to create an awareness of the surroundings (or to create the feeling of that). As this is central to the way the device should work, if a device would fail, to produce this effect after some time of adjustment, then the design would be a failure. After breaking this down, it was found that this goal consisted out of two opposing factors: creating an understanding and depicting the surroundings. The more detailed the description of the surroundings are the harder it is for a user to process the information. Similarly, the simpler the information is, the less precise is the depiction of the surroundings, possibly omitting important details. When it came to weighing those two concepts against each other, it was found, that from what was know about the use case and the user as well as from the last test, that especially the user centred needs are more focused on giving people something that can be easily understood, rather than something that is very detailed. For example in interviews, it was learned that users do not necessarily want to know what kind of shop their are currently passing, but rather want to understand that they can walk straight without bumping into things. Only the really concerning perception of the angle of obstacles found in the last test was an issue, that indicated that a bigger focus on the detailed depiction of the surroundings might be necessary.

5.2.2 New ideas

With this information, another brainstorm with the team was done and d three new viable ideas for a faster and simpler working language device were developed:

Idea 1: This idea imagines the grid device to be a vest, with three columns of actuators, one at each shoulder and one at the spinal column. Each of these actuators would represent one column in front of the user and would give of signal for when the column is empty and when there is an object within the column. The distance away from the user would be represented by different intensity levels rather then position. This idea is in parts inspired by the ”HaptiGo” device of Prasad et al. (2014).

Idea 2: This idea imagines a similar working concept to the previous idea. However it puts the actuation at the abdominal region of the user with a belt. The argument for this concept would be that the abdominal region would either be more clear or more intuitive to the user.

Idea 3: This idea remains closer to the original concept of offering the user a grid to convey information, but speeds up the process by printing each row at once. Additionally to make the device less overwhelming and confusing, it was suggested, that the device should be at the low side of the feet, as these are part of the active sensing area according to Zeagler (2017), and therefore might be more capable of handling complex information, rather than the back. This idea was very critically assessed, but was build on a very novel idea non the less, and offered an interesting opportunity to the previous ideas.

Ideas for the tacton object system: Beyond that, two new modes of how the object tacton could be integrated into these new ideas were discussed. While they are connected to specific ideas for the grid device, they are actually easy to interchange for each idea. First, a passive mode was discussed, in which a button would toggle a mode in which the object tacton system would work in parallel with the grid based system to show special objects whenever they appear. As this would slow down the device and would make it more complicated as well, this mode would require the user to stop and slowly look around to get more detailed information as needed. The other mode which was discussed was dubbed ”active mode”. In this mode the user could keep the button pressed and point at obstacles he was previously made aware by the grid system, and would receive more information about the object the user would be pointing at while the grid system would be paused. These ideas will be picked up again during the next iteration.

5.3 Specification

To determine which of these ideas should be developed into the final version of the grid device, this specification was approached in two iterations. First, divergent paths where taken, to explore which of the three ideas developed, would be the most promising one. Then this idea would be further specified to become the final concept.

5.3.1 Language

Since language is one focus of this iteration and there was a significant lack of information, of how the design and implementation of such a language should work, it was considered to be necessary to do some extra research on the basis of languages and their basic components. Considering the nature of the GP and the current state of the project the focus was put on understanding language from a technical perspective, to utilize its capabilities and to design a code which was able display all of the languages capabilities if needed. With this designers could create and select any possible word within the haptic language and be certain that the system capable of to communicating this word.

First a feature set was defined for the language:

- The language should be able to express through buzz patterns with varying intensity and duration.
- The language should be able to express each of these patterns in each possible output channel
- The language should be able to chain and save these expression together, as was explained in the first iteration, to create dynamic patterns
- The language should be able to chain those dynamic patterns together to create a queue which could be executed

- Objects as well as grid cells and their occupation need to be represented by specific patterns at specific locations
- If needed, simple buzz patterns as well as complex dynamic patterns should be playable at the same time. Their timing and should be easily adjustable for different prototypes.

As theoretical base to create the rules and components of this language, a lecture of the RWTH Aachen (2021)was found.

According to the definition given in the lecture, a grammar consists of a quadruple tuple G = (N,T,P,S). Whereas N= Non-Terminal symbol, T = Terminal symbols, P = Production rules, and S = Starting symbol. In this specific case S was omitted. Therefore G became G = (N,T,P).

First terminal symbols can be created. According to the feature set these should contain Duration D, Intensity I and Repetition/Pattern R.

D can be defined to be between 400ms and 1400 ms. This range ensures that a symbol is not too long and not to short to be properly printed. To make the following part easier an increment size of 200 ms can be assumed. Therefore P = (400,600,800,1000,1200, 1400).

It can be designated to contain three levels. This was influenced by tinkering and by a suggestion by the critical observer to not provide more than 3 intensity levels. Therefore I = (weak, medium, strong). Lastly the pattern R was decided to be limited to either 1 pulse, 2 pulses or 3 pulses within the given duration. Therefore R = 1, 2, 3

From these terminal symbols an alphabet A can be created. A= 6*3*3 = 54 characters C . Each character C in this alphabet is defined as a triple tuple of C = (D,I,R).

To form higher non terminal symbols from this alphabet, the first step is to take the output channel P into consideration. For this a production rule, which gives each character an output channel P can be added. The ESP32 can handle up to 11 output channels. Therefore P = (0..11). These can be handled as a form of accentuation to create a syllable S Therefore S = (C,P) in which C x P = 11* 54 = 594 possible syllables, which can be generated. Each syllable is defined as a tuple of (C, P).

From this further production rules can be derived to form words, representing chained syllables or ”dynamic patters” and sentences representing a queue. A word W would consist out of an array of syllables, with the production rule of W = (n*S). Separate lists for words for objects and words for cell values will be created.

A sentence would consist out of words for cell states and words for objects chained together in from the code defined order. To set a standard, the cell value should be put first and then the objects within this cell should be put. To limit the amount of objects, which can be transmitted per cell an arbitrary amount of O can be set to contain up to 3 objects per cell. Therefore, O = (0..3). With this, the production rule of the sentence Q can be set to be $Q = (n*(W_{cell}+ O*W_{object}))$.

Lastly each word in a sentence as well as each syllable in a word should receive a number to show which order in a word or sentence an element should have. This way, words and characters can be printed simultaneously.

These rules can be used to structure the way, the code deals with information and the output of the code can be defined by adding or changing words or characters in their corresponding arrays. Thus languages which focus on intensity or patterns or durations can be created, as well as languages which use complex elaborated symbols or simple signals. The limits of the language are defined by the utilized character and word combinations.

A last, additional functionality which should be added is the ability to allocate locations for grid words automatically at will, such that it can be avoided to repeat the same words for different grid cells.

The structure can be seen in figure 5.1.

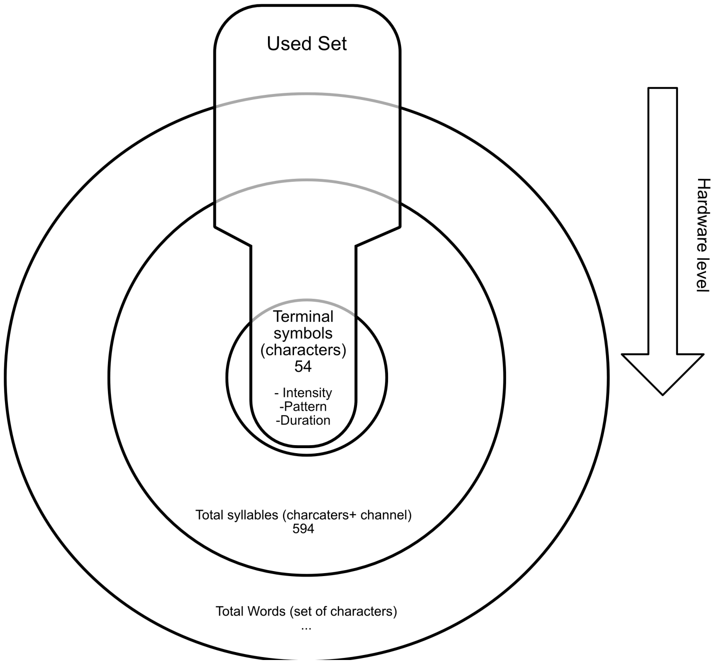


Figure 5.1

5.3.2 Evaluating the ideas

To understand how to test and choose amongst the newly generated ideas, under the consideration of many of the different design criteria found in the previous iteration and the background research, a guiding framework was developed to link design dimensions to design criteria. From this a deeper understanding of the strengths and benefits of each prototype can be developed and open questions can be identified.

5.3.3 Design Framework

The following framework was created out of technical design dimensions, in which decisions connected to the device and the language can be made, and all known design criteria from the user centred research, interviews and desk research.

In a first step for creating this framework, the criteria and design dimensions were listed and categorized (Appendix E).

The design dimensions for the device were categorized as dimensions, which either affect for the haptic language, the physical device, and the resolution specifically. For example the chosen body position and the possibility of dynamic/intuitive patterns were categorized to be relevant dimensions for the design of the language.

The design criteria were categorized according to their nature. Criteria, which promote intuition, based on the criteria found in the background research, were categorized as such. Categories for design criteria were criteria following different code types, intuitive design criteria, criteria for design for visual impairment, design criteria for wearability, technical design criteria and usability design criteria.

In a next step, these categories got matched to show dependencies in between design criteria and design dimensions. For example criteria, which are created by the chosen code being either direct or complex, such as which body regions seem to respond well to the chosen code, relate to the language design dimensions as they influence whether the chosen body part for the idea fits the code. Similarly, the usability demand of the system working fast, has an influence on the language dimensions which influence the speed of the system to transmit information, such as frequency and bandwidth.

A system which is faster would better fit this design criterium, but might be a worse fit for the design criterium demanding a reasonable slow communication to ensure the best possible understanding on the user side. This shows, that each idea with unique decisions in different design dimension might excel in some design criteria from a certain perspective and might be lacking in others. Understanding these unique qualities can help to search for specific factors in user tests and to finally make a conclusive decision. The mapping of the categories can be found in figure 5.2.

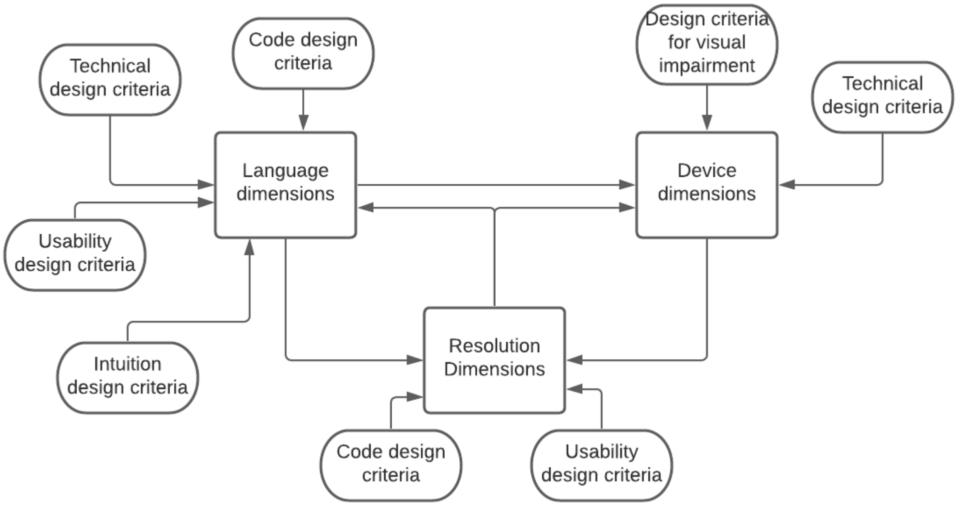


Figure 5.2: Design framework overview

Since this iteration focuses specifically on the language, the language was considered the most important set of design dimensions. Other dimensions such as wearability seem to be more important for later stages of the device. Therefore, only the language dimensions were analysed in detail to be functional as a framework for analysing the given prototypes. The result can be seen in figure 5.3.

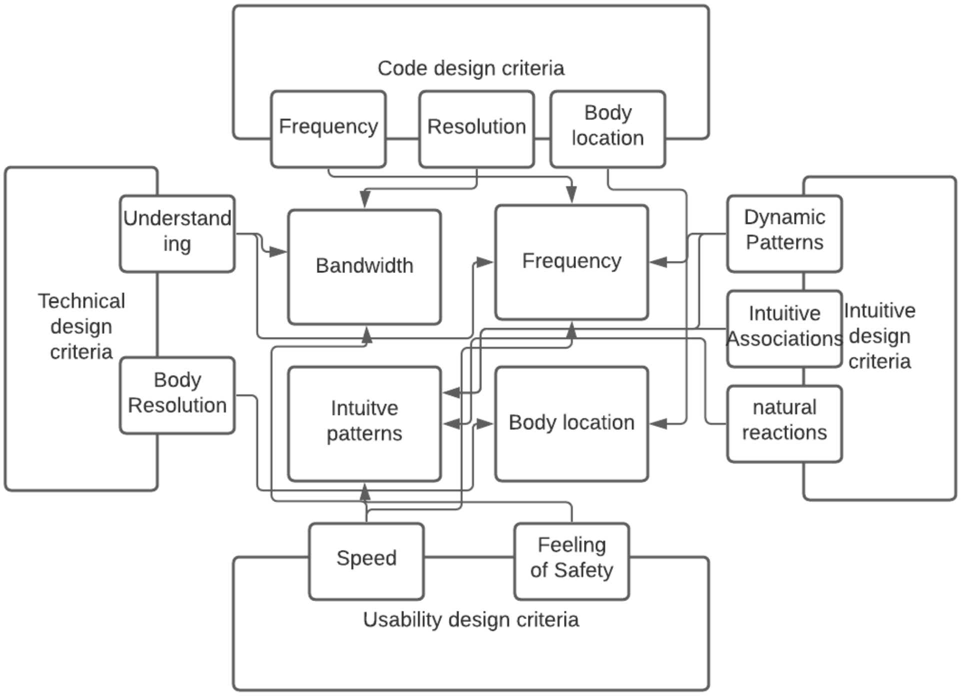


Figure 5.3: Language specific design framework

The design dimensions, which were chosen for the language are bandwidth, in how much information is being transmitted to the user simultaneously, frequency/speed, in how fast consecutive bits of information are, the inclusion of intuitive patterns, in whether some form of intuitive pattern is used, the chosen body positions, the frequency of interaction, which is encouraged or required between the device and the user, and lastly the number of parallel devices. These last two dimension were later omitted, as for all ideas which need to be compared these dimensions were shown to be equal.

These dimensions were mapped to the code related design criteria, the technical design criteria, the usability design criteria and the intuition design criteria. For the technical design criteria, the maximum level of understanding, a human is capable was added as a criterium and the available touch receptor resolution for the corresponding body part was added as another one. For the code related criteria, the body region fit for the code type was added as one criterium, and so where the frequency requirements and the resolution requirements, which were found in the background research. Complex codes require a low frequency and direct codes a decently high resolution, to be clear to the user. For the intuition criteria, it was added, whether there are dynamic symbols used for the language, whether intuitive associations were used for the language and whether natural reactions where utilized to increase intuition and understanding. Lastly for the usability criteria the speed requirement was added and on whether the design would inspire a feeling of safety within the user. These criteria were mapped as can be seen in figure 5.3.

5.3.4 Analysis of the design framework:

With the framework established, it was utilized to uncover for each of the ideas, how well they fit certain design criteria, and where relationships were unknown still and in need of testing. As some of the prototypes showed good results in relation to some of the criteria and bad results in relation to other criteria, an additional measure needed to be introduced on top of that to compare the ideas with each other in a meaningful way. For this reason, the afore mentioned bias between the concept of understanding and the concept of detailed surroundings, was introduced as an heuristic weight, attached to each category of design criteria to show the importance of each category of design criteria in the frame of the overarching design conflict. The heuristic values, which were applied ranged between 0 and 1 and were: 0.9 for code related design criteria, 0.9, for technical design criteria, 0.3 for usability related criteria and 0.4 for intuitive criteria. This is not to say, that criteria with lower values were less important in general, but they contributed less to the overarching design conflict and to its solution as it has been described in the ideation phase. With this, the scores for each design design dimension per idea could be calculated. If a design criterium would be fully satisfied, then a value of 1 times the heuristic value would be added to the design dimension. If a criterium would be only fulfilled to a limited amount a value of 0.5 times the heuristic value would be given. If a criterium would not be fulfilled a value of 0 would be added. If values were unknown, then an estimate was used instead and a mark was made that a test would be required to solve this value. For each dimension, these scores were added and then divided by the total number of criteria per dimension, to gain one value showing a score for how much a design dimension satisfies its design criteria so far as they are currently understood. The higher the value, the better it satisfies the criteria and the more important a dimension is within the overarching design conflict. Finally the results were structure for this report as a radar graph which can be seen in figure 5.4.

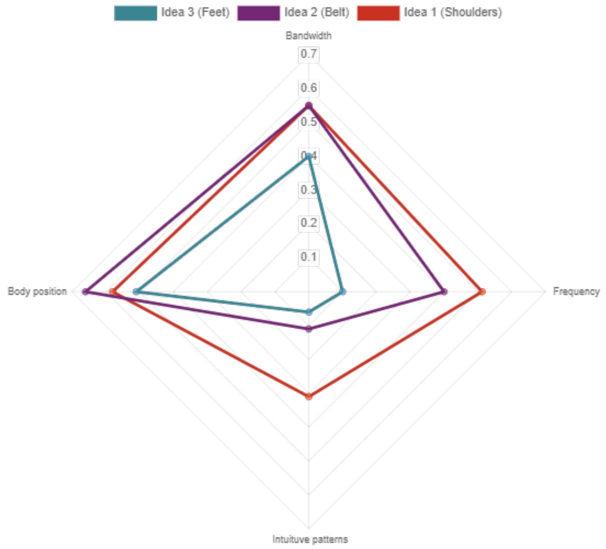


Figure 5.4: Results design analysis

As it can be seen, the shoulder prototype reached the overall highest score, which is due to the that more space is available on the shoulders, which offered the possibility to create a variant of this idea which uses dynamic patterns, such as creating an upwards motion with an extra row of actuators. This is most clearly reflected by the significant difference in the intuitive patterns dimension.

The belt idea showed the most promise when it came to the body region score. This is mostly due to the fact that the body region is the most well known region for direct codes.

Lastly, the foot grid idea showed the least amount of promise, as scores were generally the lowest. This was mostly due to the fact that not much is known about this form of haptic stimulation and that with the high bandwidth of the device, the understanding was estimated to be low.

Criteria, which were found to require more research, were the understanding, the feeling of safety, and whether users would have certain natural reactions or intuitive associations with the prototype. A user test could attempt at finding answers for these open questions.

Lastly it was noted, that for the planned test a fourth prototype, should be included. The shoulder prototype idea should be split into a static and dynamic alternative, to investigate whether the benefit the inclusion of intuition design criteria should bring in theory, can be shown in a practical test.

5.3.5 Prototype realisation

Disclaimer: As time on the project became an issue, some steps and tests had to be moved around or run in parallel with the third iteration. This section specifically happened during and after the third iteration. For this reason some learnings gained during the next iteration were included in the realisation of these prototypes.

For the sake of testing the ideas, and to converge the paths to the best idea, three prototypes, as well as the variant of the back design, were created. Each with a unique code adjustment and a unique physical design.

First the physical layout was planned as can be seen in sketch 5.5. The design was influenced by suggestions of Zeagler (2017) to ensure a tight fit if possible.

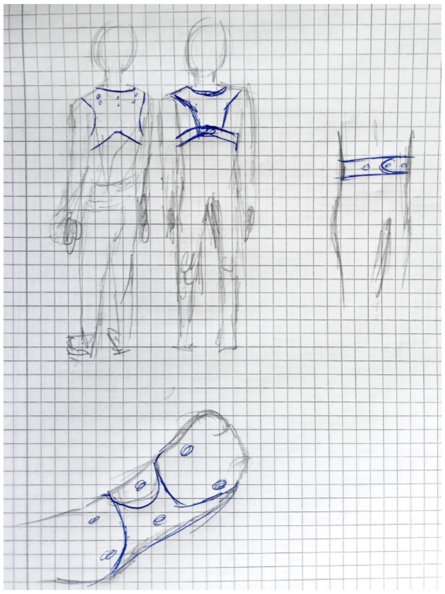


Figure 5.5

Some improvements were also added as results from learnings of the last iteration.

First the communication should now be continuous and not require a button press any more to increase the speed and the ease of using the device. Second, the design of the pockets was adjusted, so that actuators could be put in place through a hole in the fabric, rather then from the top.

For all prototypes, the minimum distance values of the placement of actuators were chosen according to the successive stimuli values of Mancini et al. (2014) and the values of Zeagler (2017). From the third Iteration the learning was implemented to change the plastic foil used to create the pockets should be switched to a plastic net to improve the clarity of the actuation and to increase the flexibility of the prototypes.

Similarly to the prototype of the last iteration, the patterns which symbolised that the a cell was free or occupied, through a single long vibration and through a double vibration, were reused in this step to symbolise a free or occupied column and would happen this time with different intensity levels depending on the distance of the object.

Lastly, as some of the prototypes would utilize intensity variations for distance, according to bounds of the language only 3 steps would be available.Therefore, objects could be either far a way with a low intensity value, in medium distance with a medium intensity or close with a strong intensity.

The foot prototype: This prototype can be seen in figure 5.6a being worn, and in figure 5.6b to show the actuator placement. Initially, the grid was planned to be four columns by three rows. Two columns per foot. However, it was only possible to add 11 actuators to the ESP 32. Therefore, the furthest row was reduced to only the two most central actuators, bringing the total number to 10.


(a) (b)

Figure 5.6: Foot prototype

The belt prototype: This prototype was the most simple design of the three. As can be seen in figures 5.7a and 5.7b the design and layout of the actuators was very straight forward. As each actuator would represent one of three columns, they had to be placed apart from each other to increase the spatial clarity.


(a) (b)

Figure 5.7: Belt prototype

The two back prototypes: These prototypes share the same form factor. A vest was designed which could hold two rows of actuators and locate them in three columns at each shoulder and at the spinal chord for spatial clarity. The centre column was slightly offset to the right, as the contact and touch sensitivity of the spinal cord are insufficient. This made it a bit more difficult to discern the middle and the right column, however, due to this decision the middle column was at least discernable at all. The static version of this prototype would only feature the upper row to communicate the state of each column in front of the user. The dynamic version would amplify this by first giving of a shorter buzz of the actuator in the corresponding lower row, increase the attention level of the user. It would then be followed by the same signals used in the static version. This way, the illusion of an upwards or outwards flowing motion should be induced to make it easier for people to understand the situation in front of them. The resulting prototype can be seen in figures 5.8a and 5.8b.

(a) (b)

Figure 5.8: Belt prototype

For each prototype a variation of the same code was used, with slight modifications and different sets of words, to make the prototypes possible.

5.3.6 Test design

To test these prototypes and the criteria discovered during the design analysis the following test was designed:

The goal of the test was, to compare the perceived performances of the different prototypes against each other. The prototypes were compared on the basis of subjective user criteria, gained from interviewing the participants after testing each prototype and their overall result of depicting a virtual environment with obstacles. The criteria, which were asked in direct questions are derived from the design analysis open questions and focused on the perceived level of understanding of the users surroundings through the device, potential natural reactions users might have felt following the stimulation, and the level of certainty/safety they felt when using the device. Similar to the first test, the participants was seated and the prototype was applied to their body onto the clothing. The procedure was as follows: After signing the informed consent form, the 4 prototypes were then applied in a random order to the participant. A virtual reality headset was also applied to the users head (the screens within the headset stayed off/black for the tests, as the headset was only used as a sensor to track the participants head orientation and as a blindfold for the user). The participant was then tasked with looking around the virtual environment, which was communicated through the haptic wearable, until he/she decided to have archived a sufficient level of understanding. With in this virtual environment two boxes were placed, which ought to be identified by the participant. Participants were then tasked with making a drawing of the environment and asked questions about their perceived understanding, their sense of security about relying on the device and whether they experienced some natural associations/reactions to the stimulation. After that the procedure was repeated for every other prototype. The participant was not recorded and no personal information was collected, leaving them completely anonymous.

The VR headset and test program was provided by the team member Tim Yeung.

5.3.7 Evaluation and Convergence

The test was conducted with three participants. The detailed test results can be seen in the Appendix F. However, due to time limitations during the project, the test had to be conducted at a later point in time than planned.

General results: The overall performance of all four devices was adequate and very similar to each other. The drawings, which were only conducted with two people, show no significant differences between prototypes. Instead a learning effect was discovered between prototypes, as the last drawings show results, which resemble the original scene more closely. The amount of understanding and safety commonly stayed rather low according to the test participants, however they also seemed to improve with the learning effect.

The feet prototype results: This prototype was often described as messy and from observation, took the longest to adjust. One participant described it as more precise than other prototypes and even claimed to feel more safe with the prototype, than with others. However the other two found it too messy to be reliable. The idea managed to create the feeling of objects being somewhere,and was capable enough to produce drawings, which were close to the original layout. However, they show a little bit more variance, than the other drawings. In terms of creating a safe feeling, this prototype only succeeded for one person to a limited degree. In terms of intuition, participants all described a different way how the prototype was intuitive. One person claimed that the feet were a good choice as they are more sensitive.

Overall, this prototype performed better than expected, yet the difficulties adjusting to the prototype fit the theoretical assumption that the level of understanding with this prototype would be more difficult. while the feet seem to work a bit better than the back during the last test, this might be dependant on other factors. Concerning the level of safety, this prototype showed no significant results, although it was at least once perceived as ”safer”. The expectation, that it made people feel more insecure was not the case. However one person preferred this prototype as his favourite.

The belt prototype: The belt prototype was received with mixed feelings. Participants felt, that the feeling of the vibrations at the abdominal region were tickling or in one case even nauseating, and it took some time to adjust to this stimulation. However, it was also described as ’natural’, after some time, indicating some form intuitive response. One person even described a slight turning motion. It was very difficult for participants to make out the distance differences, although the produced drawings are rather accurate. In comparison to the feet prototype, the time taken for adjustment, did not seem to stem from the complexity, but rather from the type of stimulus. In terms of the feeling of safety only one participant felt confident enough to be willing to take a few steps. The rest did not.

This shows that the prototype, although performing reasonably well, did not show any specific strengths either in comparison to the back prototypes. That one participant felt nauseous after using the prototype, shows that there seem to be some drawbacks with the body location.

The static back prototype: This prototype was received relatively well. One person described it as less ”sketchy” than the belt prototype. The drawn results were similar to the ones of the belt prototype. Participants found, that after some adjusting to the device it was relatively clear how it should work. One person even described it as a radar. Concerning the intuition of the device, most participants found no form of intuitive reaction and that it took a relatively high amount of mental effort to understand. Only one participant described a slight urge to turn, similar to the belt prototype, while another described a sense of urgency. In terms of safety, the back prototype was perceived more safe than the belt, although only one participant felt like it would be possible to walk around with the prototype. Lastly, some participants had problems discerning the middle column from the right column and some, but not all, had difficulties to tell the intensity differences.

This prototype seem to work surprisingly well and as a more pleasant version of the belt.

The dynamic back prototype: This prototype was received more mixed than the other back prototype. In terms of understanding it took participants a bit longer to adjust to and for one drawing yielded worse results than the simple back prototype. Participants found it more difficult to discern initially and a bit messy and thus more difficult to understand, even though after some adjusting, this feeling improved significantly. One participant was really confused by this prototype, while the others adjusted to it much better. There were also some difficulties with sensing the all actuators again. In terms of intuition, a slight upwards flowing motion was reported, and on another occasion, the feeling of having some form of antennas. In terms of safety the prototype worked similar or worse in comparison to the previous prototype.

Generally, this prototype was expected to perform the best. However, this was not the case. While the attempt to make the prototype more dynamic seemed to work, it also seemed to be confusing for the participants, decreasing the level of understanding a bit. Even more so, one participant voted it as his least favourite prototype. However, this seemed to improve rather quickly as participants got more accustomed with the prototype. Otherwise it showed to be rather similar to the static back prototype.

Convergence: With this information a decision was made, which prototype should be chosen for the final version of this part of the project. It is important to note that due to time limitations, this decision had to be made before the test was done and therefore purely on the theoretical basis.

The foot and belt devices were disregarded, as for the theoretical analysis as well as the practical test they were not as good as the two back prototypes, being either too complicated or slightly nauseating, while not brining any significant benefits to the table in terms of performance or perceived intuitiveness, understanding and safety.

The vest on the other hand was received better on average, while not showing any significant downsides. The static version of this prototype performed the best in the test, however due to the limited nature of the test, having a low sample size, using the same virtual environment per test and a strong learning effect between test runs, one can argue that this does not equate to being the better prototype. Additionally, some participants adjusted their understanding of how the systems worked during the test, which might have influenced the performance of some devices negatively. While the understanding is important, one could argue, that given enough time with both systems, given that a learning effect showed during the different tests already, the difference in understanding would be minimal. On the other hand the intuitive additions to the dynamic prototype, despite leading to a more intuitive perception of the device, did not seem to add to the clarity of the system. Yet, it improved the perception of the environment in one case and the addition of intuitive criteria also still holds a significant impact in the theory.

A second test would be necessary to compare these two versions of the prototype in a more long term oriented test, to show whether the understanding would equalize between the two prototypes and whether the intuitive effects for the dynamic prototype yield any meaningful impact that would improve the user experience and justify their addition. The current test was not able to provide this information, besides showing that there seem to be minor intuitive effects with the prototype.

Based on these informations the dynamic prototype still seems to have more potential in the end, despite the test favouring the simpler version. Since the information of the test was not available during this decision making, the decision was made to continue with the dynamic version. After including the test results this decision was not as clear as before any more.

5.3.8 Final specification

With this decision taken, the final version of the grid device can be done.

First, the device would be inspired by the dynamic back prototype, according to the decision made earlier. The prototype designed for the test could be used as the final prototype as well. As the final version was build and used before the afore mentioned test was conducted, the prototype described in the prototype realisation subsection earlier is equal to the one, which should be specified here, with some for the previous test unnecessary elements omitted.

The full specification of the prototype device can be found here:

The final prototype should take the form of a vest designed to fit tightly around the shoulders and the upper back. Similar to the prototype in the previous iteration, softshell should be used. The device can be put in place using Velcro strips. The same actuators from the previous iteration should be used. As a learning from the 3rd Iteration, which in part ran parallel to this iteration, the plastic foil for the actuator pockets on the inside should be replaced by plastic nets and redesigned to be accessible from the back through the fabric. As a working concept, the working principle of the dynamic back prototype should be used. The design should include a PCB plate on the back which should contain connectors for the microcontrollers and the actuators, to replace breadboards and jumper wires. Since the number of actuators reserved for the grid system are 6, a total number of 5 pins should be reserved for the object tacton device. Also a space for the connector of a button should be reserved on the board.

5.4 Realisation

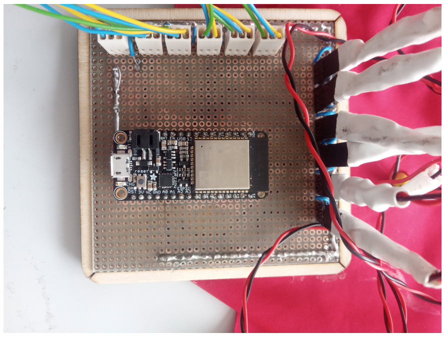
With these specifications a final device was build. The results have already been shown in the previous section under prototype realisation. An additional realisation step which has not been mentioned so far was the creation of the PCB board.

For this double sided PCB board with the dimensions of 10 by 10 centimetres was utilized. The microcontroller sockets were placed central, on the board. The sockets for the vest actuators were placed towards the top of the board. The sockets for the haptic gauntlet were placed to the left of the board. Solder lines and cable connections were used to connect all elements. The schematic can be found in Appendix G.

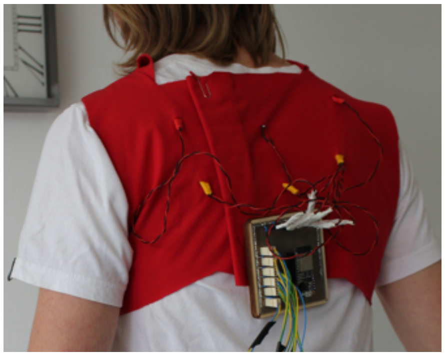
Lastly, a laser cut holder was devised to hold the board. This one was clued to the back of the prototype.

The PCB board can be seen in figure 5.9a. The final build can be seen in figure 5.9b.

During the process of building the prototype smaller tests were conducted. With these different intensity values and communication speeds were tested, to increase the clarity of the prototype.



(a) PCB board



(b) Prototype

Figure 5.9: Vest Prototype

5.5 Evaluation

To evaluate this final prototype in a more comprehensive way and to analyse how it would be working together with the other parts, a test together with the other elements created by the other team members was scheduled. In this test the vest would be evaluated with a test person working through a parcour while being blindfolded. The system would either utilize a virtual reality test environment for input or the actual sensor which was developed.

Test setup: The test setup was kept simple. After signing an informed consent form, as a first step, a test person would be asked to wear the vest. This participant would then be introduced to the haptic language while being seated to become familiar with the stimulation and its meaning. Following this step, either the sensor unit or the VR unit would be given to the participant. He/She would then be blindfolded, while a parcour build out of cardboard boxes would be placed. The participant would be guided by one of the researchers to a starting position and tasked with reaching the other side of the parcour where another researcher would use his voice to tell his position. The participant would then begin to walk their way through the parcour, with one of the researchers following the person and warning him/her before impending collisions if necessary. A third researcher would film the test. This would be repeated several times with the participant, each time changing the layout of the parcour.

Results: This test was done with three test persons. The parcour was randomized each time, however increasing difficulty levels were applied. A picture of the setup with the sensor can be seen in figure 5.10. A picture of the setup with the VR headset together with a parallel view of what the VR headset used as a source for input (the user did not see this) can be seen in figure 5.11.

Figure 5.10: Test with sensor

Figure 5.11: Test with VR

We found that the system worked surprisingly reliable. After a minor learning period initially, participants were able to navigate the parcour with little to no incidents. While participants were rather slow in the first few test runs, we also found that participants slowly started to speed up, the more they became familiar with the working of the system. Given, that these participants were neither used to navigate without their sight as they were visually able, and that participants were not given a cane but had to navigate purely with the system, this test proved to be a major success. As the system was designed to be used with the cane one could expect an even better performance with the cane. Sadly we were not able to test with people with visual impairment.

However some issues were found as well. For one, a problem was discovered, were participants would clip an obstacle barely, as the obstacle slipped the detection range. This was due to the chosen sensor angle of 45 and due to the first meter in front of the person being omitted, as this would be usually covered by the cane. The usage of a cane would have solved this issue. However we decided to adjust the angle of the system to be wider and to include the first meter in front of the user for the test purposes only, to avoid this problem better in future tests.

There were also some issues in which certain actuators were difficult to perceive due to ill fitting of the prototype on some body types, significantly different than the designed for body type. Also the middle actuator was difficult to discern sometimes.

The different distance values were difficult for users to understand.

Lastly, this test showed that there was quite an important learning effect necessary to happen, for the system to be understood by the user quickly and reliably.

Chapter 6

3rd Iteration

The next and last step in the development of a haptic navigation wearable, was done in form of the third iteration. It remains important to note, that despite this iteration starting much later than the second iteration, time limitations and hold ups in the 2nd iterations specification phase led to this iteration being completed before some parts of the previous one. This iteration contains all 4 major phases, although some only in limited capacity as a lot of the work for this iteration was based on previous iterations.

6.1 Goals

The main focus of this iteration was the development of a device which would be capable of using haptic vibrations to communicate not the position of an object but its type. The device would be meant to work as an extension for the grid based vest developed in the last iteration and should be able to communicate objects like stairs, doors and street crossings.

6.2 Ideation

As has been discussed in the ideation of the last iteration, two working principles for how this object tacton device could be integrated in the workings of the grid based vest were suggested.

The first one being a passive mode which would activate the gauntlet upon a button press and would all objects simultaneously to their depiction within the grid based system. This would result into some form of a detailed mode, which slows down the speed at which information would be usually transmitted to add the tactons for the object in between. A future variation of this could be, that each type of special object could have its own button and it could be made possible to filter for what ever object would be searched.

The second mode was dubbed ’active mode’. With this mode, the user could use informations from the grid based vest to learn about the position of objects, and then point at these objects, while keeping a button pressed. This would disable the vest and would instead make the system communicate which ever type of object the user points towards. Users could also use this to find objects like doors in the distance by keeping the button pressed and scanning the environment by slowly pointing around them. This version of the idea will be only used with the virtual reality environment within this project, as to develop the necessary sensor setup to make this system work with the camera sensor as input would not be possible on time.

For both modes the same device could be used.

The proposal for such a device, which utilizes tactons to create icons for objects, is heavily inspired by a design by Paneels et al. (2013). The device describes a device which is designed for the wrist, similar to a wrist watch. The device contains six actuators arranged in a circle on top of a monolithic structure. These actuators could be activated in different orders to create tacton patterns, with which codes or symbols for specific instruction could be create. This way, the researchers were able to successfully communicate directional information and warn users about certain objects such as doors and stairs. The device used for this project could use the same idea. However, this idea would need to be adjusted to fit the requirements and conditions of this project.

6.3 Specification

Within this phase, the concept described earlier will be taken and modified to create a device capable of transmitting complex information.

The code type: As a first step, the type of code, which would be used for such an idea was considered. As these tacton symbols would require a longer time to be played and understood by the user than the grid information and would also require knowledge and more effort by the user to be understood. Therefore, the code can be considered of complex nature, as has been described in the research chapter and should consider the learnings about complex codes. For one, the body region which was attributed in the research with complex codes were the hands. This would fit with the currently planned location of the device. Second, the device should use a low frequency to increase understanding and also should dynamic rather than static symbols, as has been shown by Paneels et al. (2013), meaning that patterns should not be printed at once but actuators should be activated after one another to create a sensation of movement.

Hardware specifications: The biggest changes from the original idea to this adaptation were hardware changes. First of, due to only five actuator spots still being available, the number of actuators to form the pattern was determined to be five vibration motors ordered in a circle, similar to a pentagonal shape. Also, for this project no monolithic structure as has been used in the version of Paneels et al. (2013), was available for this project, which would otherwise help to distinguish the vibrations. Therefore, to still ensure the clarity of the device, the location of the actuators was moved to the back of the hand, instead of the wrist. This transformed the wristwatch into a gauntlet.

Additional criteria, were, that some form of connector interface should be added to the gauntlet. This was decided for the reason that long cables would connect the gauntlet to the PCB board on the back of the user. To prevent these cables from damaging or ripping the actuators off the prototype, an interface with connectors on a PCB board should be added to the gauntlet. This way could the cables of the actuators be kept short and there would be no danger of ripping them.

Also a Button should be added to the device to enable or disable the gauntlet.

Language specifications: The words, which would be used to print object symbols in the gauntlet need to be specified as well. First a list of objects which potentially would need to be printed within this project was created. This was already mentioned once in the first iteration about the communication protocol. The objects which will be used are:

- Pedestrian traffic light / street crossings
- Roads
- Stairs upwards
- Stairs downwards
- Doors
- Other obstacle
- Low hanging obstacle

The items were marked within the communication protocol in the same order, starting with 001 for the street crossing symbol. Since each symbol would need to be dynamic, they should at least consist out of two steps. Some codes could be taken from the results of Paneels et al. (2013), as they were proven to work within their paper. These were the symbols for stairs and the symbol for door. These were adjusted to the 5 actuator layout. For other symbols, associations should be used for reference.

6.4 Realisation:

According to the specifications a prototype device was built. The resulting device can be seen in figures 6.1a and 6.1b. During the build materials and techniques of the previous sections were used. Initially plastic foil was used to create pockets for the actuators. However, since this worsened the flexibility of the device, resulting a worse contact to the skin, another material was considered. The switch was made to a plastic net material. This had the added benefit of also increasing the clarity of the device. Therefore, this material was also used for the grid devices in the second iteration.

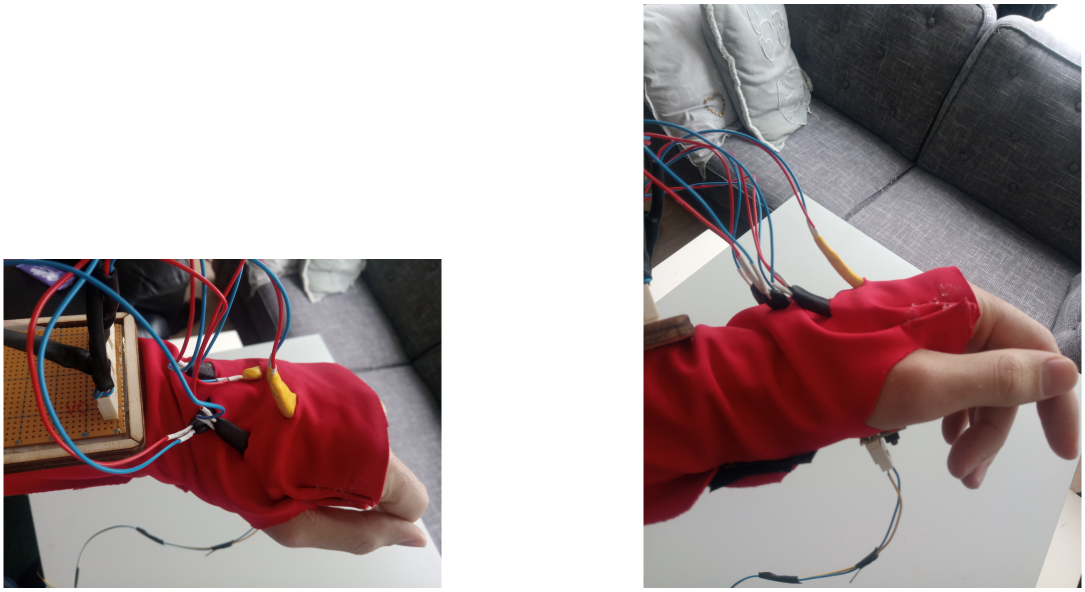


Figure 6.1: Gauntlet prototype

The button was added to the inside of the hand, at around the position of the thumb knuckle. This way the button could be easily pressed with the index or middle finger, even when holding an object like a cane in the hand, as the hand forms a tube shape when the button is being pressed.

The last part of the realisation was the creation of words, which could be used to signify objects. As mentioned, some of the codes were adapted from Paneels et al. (2013), while others were inspired by the nature or shape of the objects they represent. For example the road sign was created by having the bottom four actuators run in a circle, signifying two car lanes with different directions, as in the bottom two actuators forming one lane with the car driving from left to right, and the middle two actuators forming a lane on which a car drives from right to left.

Additionally, some program code improvements and refactoring was added. In order to make the used program more readable and more clear to review and to adjust, some slight refactoring was done. This included elements from data oriented programming models, to emphasize more clearly how the input signal gets transformed into a sentence with words, syllables and characters which can be outputted to the user.

6.5 Evaluation

6.5.1 Test

The evaluation for this prototype was done in form of a small test, which was conducted together with the large final test as well as on some instance independent of this test.

The test for this prototype was done in two steps.

First, five objects would be taught to the user in random order. They would be demonstrated and explained. Then in a second step, these objects would be played in a random order, and participants would be asked to identify them. The success rate was documented anonymously. There were two reasons for the low number of objects which would be taught. The first reason was that since this test was run in combination with the final test, only a limited amount of time was available and a limited amount of objects were necessary for the users to be prepared for the following tests.

The second reason was, that initially users showed difficulties remembering and reciprocating larger numbers of objects in such a short time, due to the limited capabilities of humans to remember a list easily. This would have impacted the test results, as memory gaps and not the ability to tell object symbols apart would influence the success rate of the test.

6.5.2 Results

A total number of eight people were tested using the test described above. The average rate at which a symbol was recognized correctly is 82.5 percent or rounded 4 out of 5 objects (Appendix H). This score, despite the limited sample size of the test serves as an indication, that the concept for the gauntlet works and can be learned relatively easily. However, participants needed some time to recognize the objects, as they needed to listen to it actively and required some time to understand the stimulus. This again indicates, that in order to use the device on a regular basis, users would need to learn, not only to remember the object patterns, but also to listen to the stimulus.

Beyond that, a number of issues and feedback was collected. For one, some of the participants had very different hand sizes. This influenced the fit and the clarity of the device. It was also noticed and remarked by some participants, that they mainly used the patterns to distinguish between objects and less the allocation. This information could be used for future prototypes.

Chapter 7

Final product

Within this section the final product, result of all three iterations, will be summarized and its final components will be discussed.

The device, which was created serves as the central part of a product, which aims to provide users with visual impairment with more awareness of their surroundings. The goal is to enable them to make more informed decisions and to help them orient themselves in new and complicated environments and to make them feel more safe. The device was not designed with the intend to replace the cane but rather to extend its range.

7.1 Overview

The system works in the following way.

A sensor (developed by Kai Ferdelman) scans the environment between 1 meter and 5 meters away from the user and saves the information in a grid. Information is collected about whether a grid cell is passable or not and certain types of important objects such as stairs and doors are being saved as well. The information is then divided into sets which are being requested by a haptic wearable worn by the user through serial communication.

The function of the haptic wearable is structured as can be seen in figure 7.1.

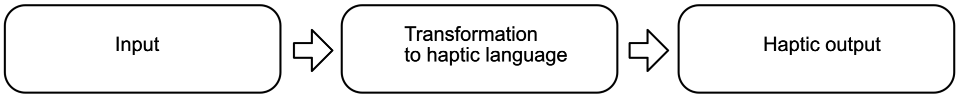


Figure 7.1: System Structure

The system takes the input containing environment information and saves it in form of grid cells and objects. This information is then being filtered and transformed in a logic unit, before being translated into the words of a haptic language. These words are then chained together according to a predefined rule to form a sentence queue. The sentence queue is then being read by an output function, which processes the information contained in each word step by step and prints each haptic character at its corresponding output channel.

This process can be seen in figure 7.2.

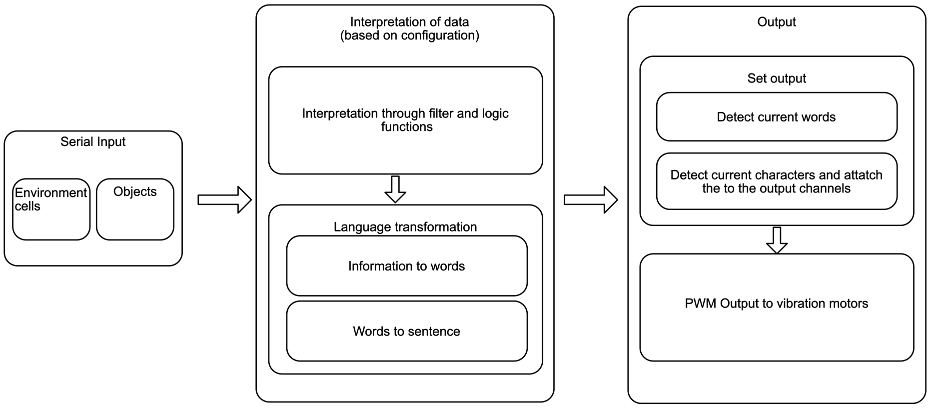


Figure 7.2: Processing Structure

The output is distributed over two separate devices worn by the user. A haptic vest which uses vibrations at the shoulder to output the environment cells in front of the user and their status of occupation, and a haptic gauntlet, which can be added by will through the use of a button which uses an assembly of haptic vibration motors, to convey tactical icons, tactons, of special objects of interest. The device is controlled by an ESP32 based microcontroller and uses coin vibration motors.

Figure 7.3: Complete prototype

7.2 The vest

An overview over the working principle of the haptic vest can be seen in figure 7.4.

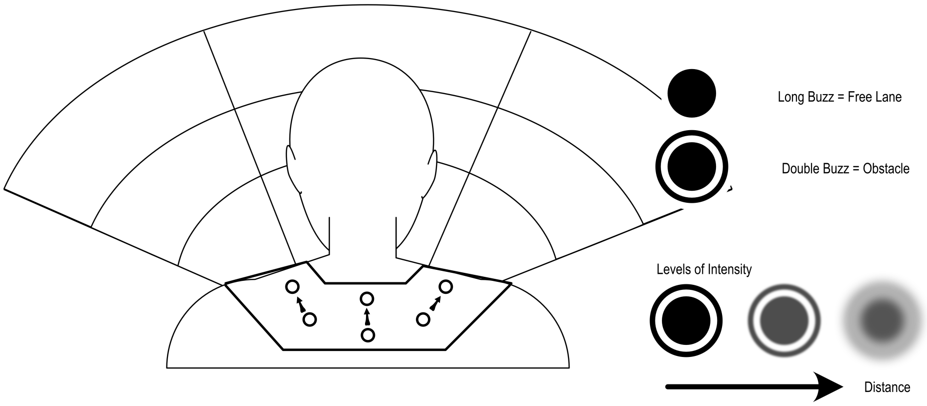


Figure 7.4: Vest overview

The vest utilizes 6 vibration motors distributed over the back, as can be seen in the figure. Each column represents the column in front of the user. The vest includes a dynamic outwards flowing pattern in which first, the lower row actuator of the column gives of a short buzz, before the top row actuator buzzes in one of two ways. If the column is free the actuator gives of a long buzz. If the column is occupied by an obstacle the system gives of a double buzz. The distance of the object to the user is communicated through 3 levels of intensity. The further away an object is the less intense is the top actuator buzz. Each column is printed separately in order.

7.3 The gauntlet

An overview over the working principle of the haptic vest can be seen in figure 7.5.

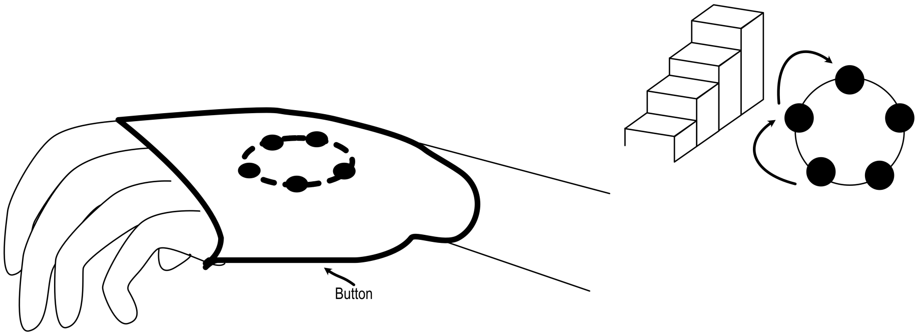


Figure 7.5: Gauntlet overview

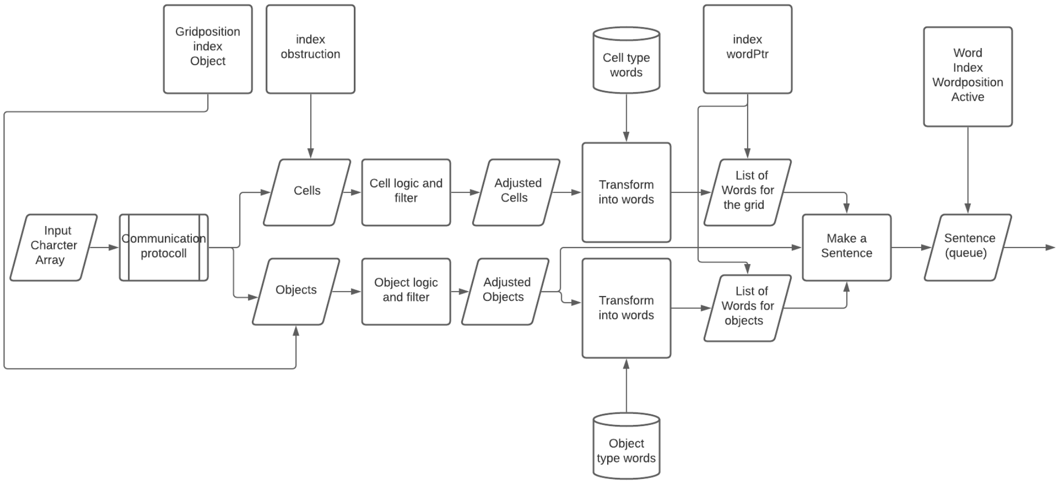
The gauntlet uses a working principle inspired by Paneels et al. (2013). Five vibration motors are arranged in a pentagonal shape resembling a circle on the back of the hand. The gauntlet uses these actuators in dynamic combinations to produce patters which resemble special objects. For example having actuators activate one at a time on the left side going upwards represents a stair going upwards. These symbols are being used to inform the user of which type of obstacle he/she might encounter. The gauntlet is being controlled by a button on the bottom side of the glove. Depending on the mode the button either works as a toggle to print the objects together with vest at once, or the button can be kept pressed by the user to only print the object the user is pointing at. The latter currently only works with the combination of a VR handheld controller to track the hand position.

7.4 The language

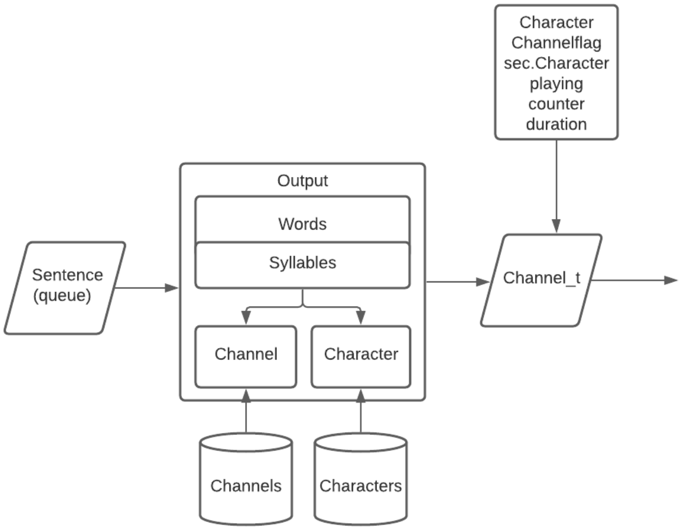
The language, which powers both of these devices is a uniquely created flexible haptic language. The language uses a triple tuple of Pattern, Intensity and Duration to create a total number of 54 total haptic characters. These can be printed through every available channel (in the case of this project 11). The combination of a channel number and a character is called a syllable. A combination of syllables can be formed to words, which equate to certain informations, such as the name/type of an object or the presence of an object. They can be combined into a sentence which is then being read by an output function. If a grid is being used for the output, the possibility to set the position of a word dynamically is given. Potentially this language can be used for more different devices or to test more possible languages, such a purely pattern based language, and has been used for other types of languages in this project to certain degrees.

7.5 The code

The code which has been developed for this prototype, follows a data oriented programming structure and is task based. Input data is being adjusted and transformed into word type data elements according to the available word list. Word type data structures contain syllables, which consist out of character type objects holding information about the physical output, and channel ids. A queue (sentence) is generated with these words according to logic and send to an output function, which reads the word character by character and adds the correct character type information into an channel type data structure, which serves as the repository for a task which manages the hardware output of the system. This process can be seen in figure 7.6a and 7.6b.



(a) Translation



(b) Output function

Figure 7.6: Data flow

The codes is divided into tasks, which are being managed by a task manager library, activating them only if needed. The microcontroller can go into a sleep mode if not occupied by any task. The used programming language is the C based Arduino language for ESP 32.

7.6 Example

An example can be given how the system works as one. Assuming that there is an upwards stair in 5 meters distance at the left side of the user. The sensor would detect the presence of such a stair within the left column at the furthest distance. This information is being send to the haptic actuation device and can be read as such: ”An object is at the current (left) Set far away. This object is a stair going upwards.”. After removing other unnecessary data the haptic actuation device translates this information into a sentence of the haptic language using haptic words. Another task, reads this sentence and delegates channels to output each haptic word character by character. The information is being encoded in pattern duration and intensity and set to a specific output channel. The user first perceives on the vest the left lower actuator giving off a short buzz, before the left upper actuator gives of a weaker double buzz. If the gauntlet is in use, this is followed by pattern of three short buzzes on the hand signifying the stair.

Chapter 8

Final test

The project was concluded with a final test, using the latest version of the device and all of its components. The test was conducted together with the entire team. The test was conducted on two separate occasions due to time limitations. Some minor quality of life improvements were made in between the occasions.

8.1 Test

The test, which was conducted, consisted out of three phases. In the first phase, the user was introduced to the haptic device and its language. The working principle of the vest and gauntlet were explained and tested by the user. The final test for the third iteration, which tested the workwise of the gauntlet device and was described earlier, formed a part of this phase.

In the second phase of the test, the user was equipped with the sensor and blindfolded. A parcour made of cardboard boxes was created and the person was tasked with navigating to the other side of the parcour. The user would be accompanied by a researcher to warn him in case a collision would be about to happen. Another researcher would use his voice at the end of the parcour to serve as a target. This would be repeated at least two times. The process would be filmed. In a next step the parcour would then be rearranged and objects, which could be recognized by the sensor were placed around the user. The user was then tasked with identifying and navigation to that object.

In the third phase, the sensor would be replaced by the VR headset. The used test program contained three virtual environments, which were modelled after the three chosen scenarios, determined in the early phases of the project. Finding a street crossing in a city, finding a store entrance in a mall and finding a staircase on a train platform. The scenarios were played one by one by the user. They would have to find the objects of interest and navigate to them within the virtual environment using only the haptic wearables.

After this, the user would be asked to fill in a questionnaire containing open questions and questions on a seven-point Likert scale. The questions revolved around the opinion of the user on the device, its wearability and function and the perceived effects the device had on them.

The test was conducted on two separate occasions. On the second occasion the second phase of the test was omitted. Also some bug fixes and the addition of new word for communicating the user that he/she would be clipping inside of a virtual object happened. A total number of five participants went trough the entire test, while two more only tested parts of the test due to time limitations.

8.1.1 Limitations

The test sadly came with some limitations. For one, the long nature of the test led to the test protocol being difficult to follow and to some steps being executed in the wrong order, with delays or with errors. Also for the first occasion, a few bugs concerning the output of the device, which were not discovered in previous tests, as well as faulty connection, worsened the user performance. These were fixed for the second occasion. These issues could have been found by a proper pilot test, which was skipped due to the time necessary to conduct it.

Another limitation for this test was its low sample size and learning effects during the test.

Last, since the system was found to have a strong learning curve, a test with more experienced users was not possible. This also influenced the results, as only the performance of new user were tested. Test participants were also not visually impaired and did not wear a cane, which the system was designed to work with.

8.2 Evaluation

Despite some of the limitations of this test, the results seem very promising. Not only were the results of the second phase of this test successful in showing that the system is capable of making blindfolded people evade obstacles on their own and showed that people were able to identify objects using the build device, but also the results of the third phase and the questionnaire were confidence inspiring.

Concerning the second occasion for the test, results showed that after a steep initial learning effect users slowly had an easier and more successful run. According to the analysis made by Tim Yeung, no participant at the second occasion managed to beat the first scenario. The first scenario also took the longest on average and had the most incidents of users clipping into objects. On the other hand, scenario 2 and 3 were both beaten an decreasing amount of time and with little to none incidents. This shows as well, that given a certain time to learn how to use the device, the concept works well. Tests results from both phases as well as previous tests, indicate a promising performance given enough time to adjust to the system.

This can be seen in the results of the questionnaire as well. The summarized and averaged results, grouped into topic areas for the questionnaire can be found in Appendix I. Generally, the response shows that the device was viewed as promising by most of the participants and attributed a good experience of around 5 out of 7 on the Likert scale. Participants also wrote they were surprised by how well they adjusted to the device after an initial period, to the point were some claimed a certain level of safety within the lab environment. Some of the points, which saw common criticism, were the fit of the haptic devices for some body shapes and the connected issue that certain haptic signals were difficult to feel because of it.

The mental effort was rather high, also caused due to a sometimes ill fit of the devices. Especially the hand prototype had caused some issues for some participant as it required a lot of concentration. Some of this mental load might have been produced by the bug. Also with an increasing learning effect, participant claimed to become more accustomed to the signals.

The physical effort and wearability of the system were generally rated to be very good. The device was perceived as light and comfortable and avoided the production of sweat, except for some body shapes. Professional improvements might ensure a better fit generally and for some specific body shapes.

Concerning the understanding of the surroundings, responses were rather mixed and ranged from overwhelmingly positive responses to some sceptical responses. However, the actual level of confidence in the participants understanding of their surroundings was rather low with the average only being 2.8 out of 7 on the Likert scale. The device itself was rated as medium in terms of clarity and some elements which were considered difficult were the perception of intensity levels and the gauntlet.

Nevertheless, participants reported a certain level of safety and testified that with an increased amount of time their safety and confidence, as well as their understanding of the device. One person even reported the wish to be part of a longer test to learn more about the system.

In terms of intuition, the device was rated to be rather intuitive. Association with the stimuli were only sparely reported, as one person felt like the vest worked as if somebody was tapping on their shoulder. In terms of the gauntlet, the signals, despite being complicated were mostly understood and users also understood the inspiration of the patterns. Users also reported to develop intuitive responses to the prototype during the test. However not all of them corresponded with the actual meaning of the stimulus.

This response shows that the device, despite being a little rough to use and learn in the short period of the test has definitely potential. Especially given the limitations of the test. Users seem to adjust to the system, understand it at some intuitive level and use it to understand and navigate their environment with relative confidence, given that the device works as intended on their body and enough practice experience.

Chapter 9

Discussion and Conclusion

Overall the results seem very promising. The outcome is definitely a prove of concept and shows a lot of potential given a user spends some time to learn the system. It was able to give users an overview over their immediate surroundings and helped them to evade obstacles without any other measure of support. The system also showed some signs of intuitive responses being developed and seemed to to provide users with the ability to detect and even identify obstacles and points of interest in real and virtual scenarios. Criteria, which concern the design for users with visual impairment were partially met, such as wearability, but also other criteria such as discrimination need to be considered in possible future iterations. The materials used so far are also cheap and widely available.

In general, the chosen design decisions seem to match well with user centred design requirements, making the code more understandable and fitting to real world user problems and demands such as speed. The utilisation of iterations contributed to avoid the development of a too slow system and impractical system and helped to explore different possible solutions through divergent paths. While some of the user tests lacked a form of scientific validity and quality to convincingly prove some effects, the collected results clearly indicate successive improvements of the system step by step, up to showing promising results. Additionally, areas to improve the prototype further could be identified, such as the improvement of the clothing design and the way intensity is utilized. Beyond just the prototype a working haptic language was developed, which holds the potential to be further applied to other projects, with minimal changes to the code.

Sadly some time limitations were encountered, which had a negative impact on some of the testing, as well as on some of the timing within the iterations. While the absence of a fourth team member was well picked up by this project, the significant scale of the project, its many steps , as well as some initial delays concerning the user research and the ethics permissions, led to disturbances within the planned time line. Despite these issues however, a well designed and working as well as multifaceted end product was created, which combined user centred design practices with hardware and software design.

Concerning the final research question: *"How to design a wearable to enhance the navigation capabilities of people with a visual impairment using haptics?"* An answer in form of the project was found. It was possible by combining design and technical fields to create a device which holds potential to support people with visual impairment, to empower them and to have an impact in their daily lives, while remaining a unique and adapted design solution. To design such a device a wide number of factors have to be considered and brought together, to not only create a device which works, but also which has the potential to be liked and used by its designated user group. It would be very interesting to pursue future work.

Limitations: Of course there are some limitations to the achieved results.

Primarily, it was not possible, to do a final test with people from the actual user group. While contact was established with user and parts of the project were developed along side user feedback, an actual user test would have been a valuable part of the project. Due to this reason as well, some adjustment to the function needed to be made to work around the absence of the cane and of users capable of using the cane.

Another limitation was found to be the given time frame. Hold-ups within the project were able to cause issues along the way, but also the overall scope of the project proved to be ambitious for the time available, which led to some corners being cut, such as proper pilot tests, to ensure that tests would be possible.

Lastly, the fact that people have different shapes and body sizes, which could not all be accounted for, as well as my own lacking skills in regards to tailoring led to some inconsistent experiences of test people, with some actuators only being connected loosely or not at all to the users body. This in terms produced some inconsistent results in regards to the tests.

However despite these limitations a promising base was able to be created upon which future iterations could be build on.

Future work It would be worth to pursue this work further in some form of another. Additionally to some improvements which could be made in terms of how distance utilizes intensity and how for example the gauntlet could be simplified in different ways, it might just be interesting to run a test which gives users more time to learn and understand the system, perhaps even test it in real life situations.

Further the prototype could evolve to a next level, by utilizing more professional tailoring and improving the portability by removing wires and adding wireless capabilities. Also adding hardware sensors to truly enable the active version of the haptic gauntlet could be another avenue of development.

Most importantly though, the system would need to be tested with people with visual impairment, as their missing verdict might be the most pressing improvement which can be made.

In the end it can be said with confidence, that with more work, this promising concept could be developed into functioning technical solution, which has the potential to impact the lives of many people with visual impairment.

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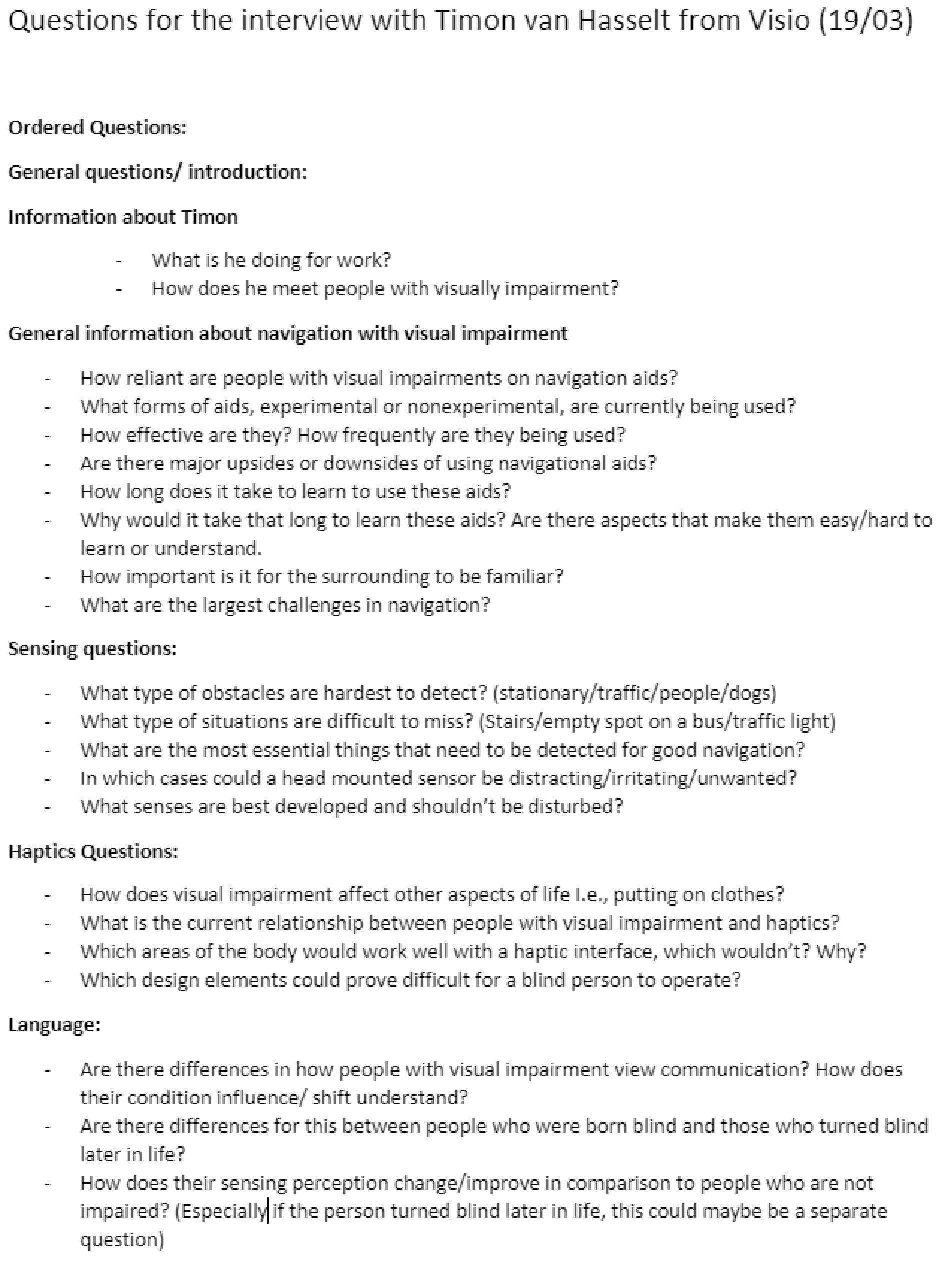
Appendices

Appendix A

Interview structures

A.1 1st Interview



Questions for the interview with Timon van Hasselt from Visio (19/03)

Ordered Questions:

General questions/ introduction:

Information about Timon

- What is he doing for work?
- How does he meet people with visually impairment?

General information about navigation with visual impairment

- How reliant are people with visual impairments on navigation aids?
- What forms of aids, experimental or nonexperimental, are currently being used?
- How effective are they? How frequently are they being used?
- Are there major upsides or downsides of using navigational aids?
- How long does it take to learn to use these aids?
- Why would it take that long to learn these aids? Are there aspects that make them easy/hard to learn or understand.
- How important is it for the surrounding to be familiar?
- What are the largest challenges in navigation?

Sensing questions:

- What type of obstacles are hardest to detect? (stationary/traffic/people/dogs)
- What type of situations are difficult to miss? (Stairs/empty spot on a bus/traffic light)
- What are the most essential things that need to be detected for good navigation?
- In which cases could a head mounted sensor be distracting/irritating/unwanted?
- What senses are best developed and shouldn't be disturbed?

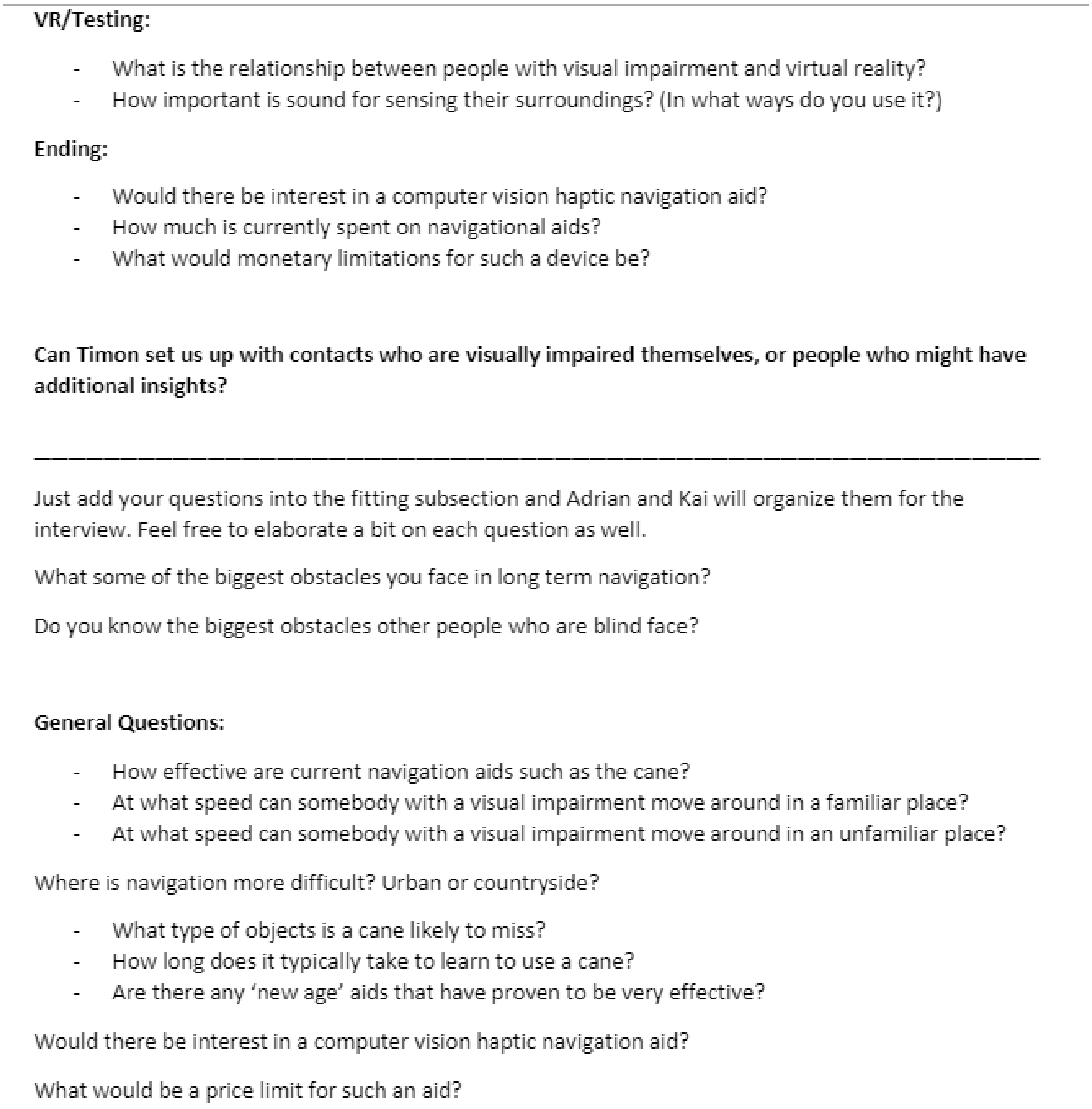
Haptics Questions:

- How does visual impairment affect other aspects of life I.e., putting on clothes?
- What is the current relationship between people with visual impairment and haptics?
- Which areas of the body would work well with a haptic interface, which wouldn't? Why?
- Which design elements could prove difficult for a blind person to operate?

Language:

- Are there differences in how people with visual impairment view communication? How does their condition influence/ shift understand?
- Are there differences for this between people who were born blind and those who turned blind later in life?
- How does their sensing perception change/improve in comparison to people who are not impaired? (Especially if the person turned blind later in life, this could maybe be a separate question)

Figure A.1



VR/Testing:

- What is the relationship between people with visual impairment and virtual reality?
- How important is sound for sensing their surroundings? (In what ways do you use it?)

Ending:

- Would there be interest in a computer vision haptic navigation aid?
- How much is currently spent on navigational aids?
- What would monetary limitations for such a device be?

Can Timon set us up with contacts who are visually impaired themselves, or people who might have additional insights?

Just add your questions into the fitting subsection and Adrian and Kai will organize them for the interview. Feel free to elaborate a bit on each question as well.

What some of the biggest obstacles you face in long term navigation?

Do you know the biggest obstacles other people who are blind face?

General Questions:

- How effective are current navigation aids such as the cane?
- At what speed can somebody with a visual impairment move around in a familiar place?
- At what speed can somebody with a visual impairment move around in an unfamiliar place?

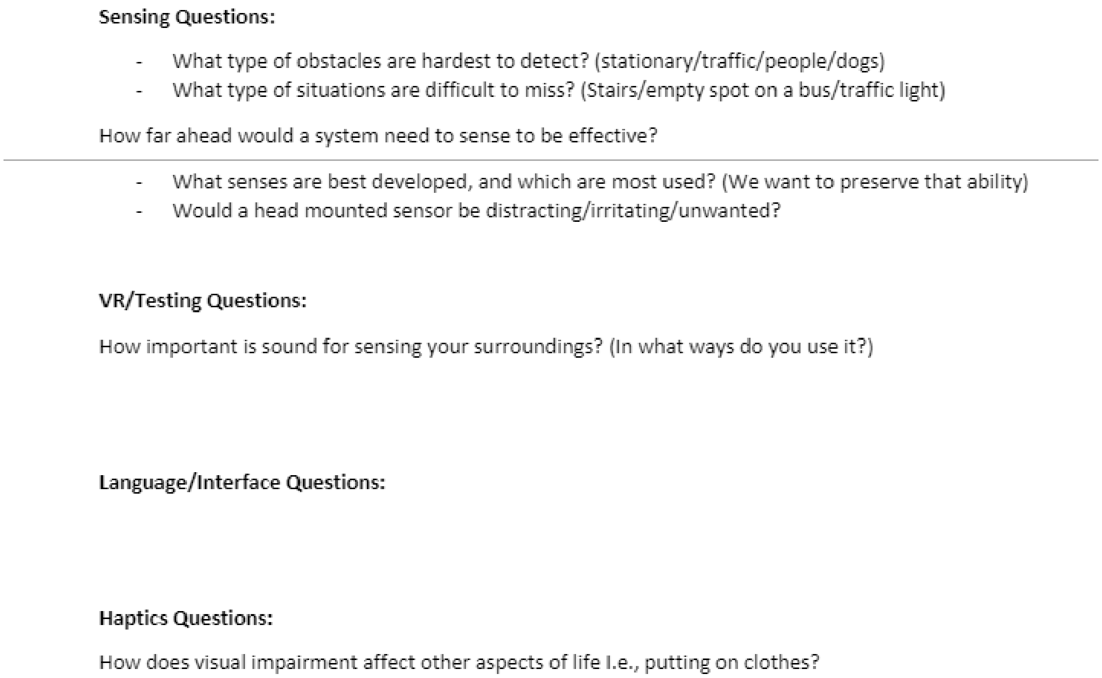
Where is navigation more difficult? Urban or countryside?

- What type of objects is a cane likely to miss?
- How long does it typically take to learn to use a cane?
- Are there any ‘new age’ aids that have proven to be very effective?

Would there be interest in a computer vision haptic navigation aid?

What would be a price limit for such an aid?

Figure A.2



Sensing Questions:

- What type of obstacles are hardest to detect? (stationary/traffic/people/dogs)
- What type of situations are difficult to miss? (Stairs/empty spot on a bus/traffic light)

How far ahead would a system need to sense to be effective?

- What senses are best developed, and which are most used? (We want to preserve that ability)
- Would a head mounted sensor be distracting/irritating/unwanted?

VR/Testing Questions:

How important is sound for sensing your surroundings? (In what ways do you use it?)

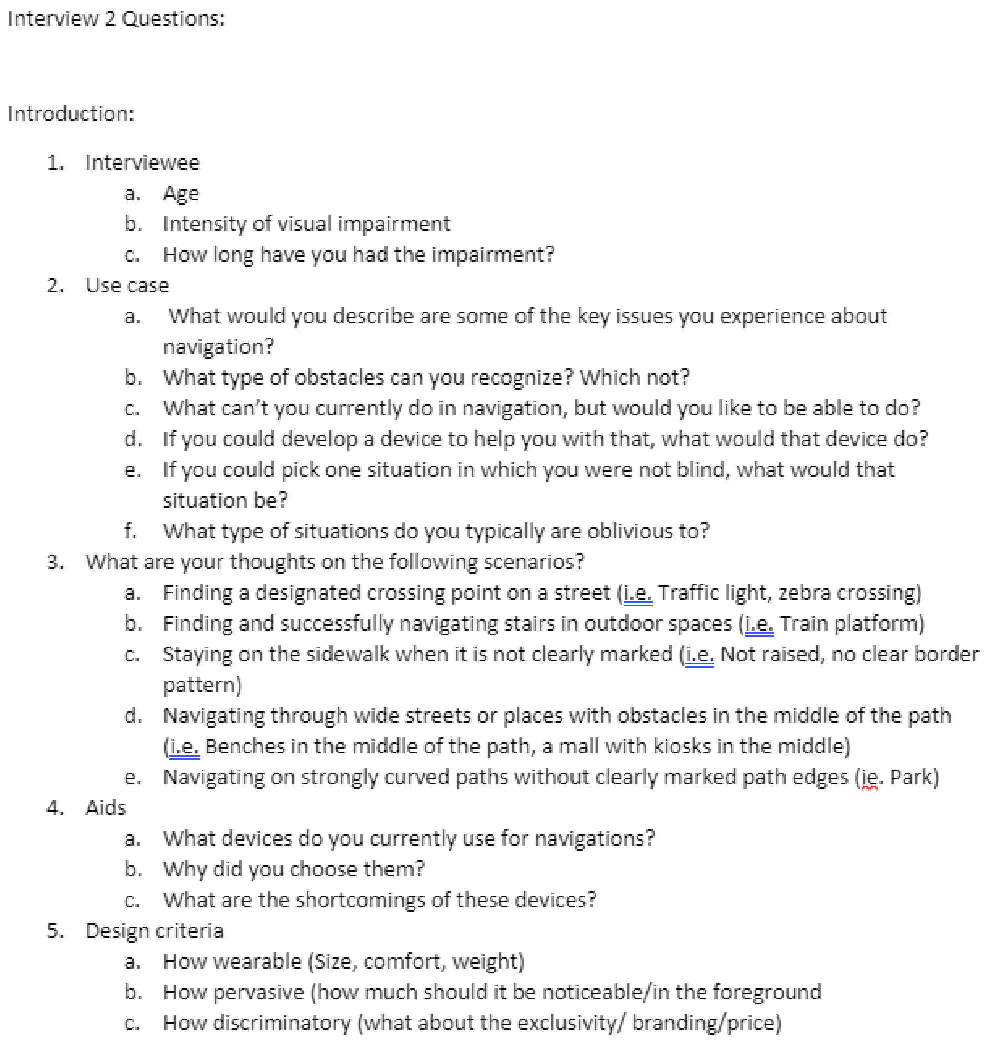
Language/Interface Questions:

Haptics Questions:

How does visual impairment affect other aspects of life I.e., putting on clothes?

Figure A.3

A.2 2nd Interview



Interview 2 Questions:

Introduction:

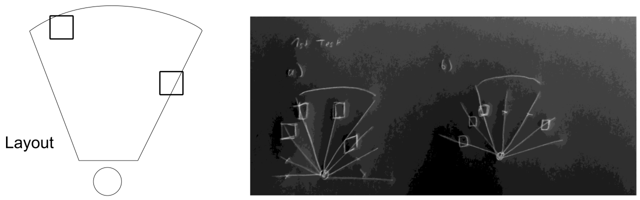
1. Interviewee
    a. Age
    b. Intensity of visual impairment
    c. How long have you had the impairment?
2. Use case
    a. What would you describe are some of the key issues you experience about navigation?
    b. What type of obstacles can you recognize? Which not?
    c. What can't you currently do in navigation, but would you like to be able to do?
    d. If you could develop a device to help you with that, what would that device do?
    e. If you could pick one situation in which you were not blind, what would that situation be?
    f. What type of situations do you typically are oblivious to?
3. What are your thoughts on the following scenarios?
    a. Finding a designated crossing point on a street (i.e. Traffic light, zebra crossing)
    b. Finding and successfully navigating stairs in outdoor spaces (i.e. Train platform)
    c. Staying on the sidewalk when it is not clearly marked (i.e. Not raised, no clear border pattern)
    d. Navigating through wide streets or places with obstacles in the middle of the path (i.e. Benches in the middle of the path, a mall with kiosks in the middle)
    e. Navigating on strongly curved paths without clearly marked path edges (ie. Park)
4. Aids
    a. What devices do you currently use for navigations?
    b. Why did you choose them?
    c. What are the shortcomings of these devices?
5. Design criteria
    a. How wearable (Size, comfort, weight)
    b. How pervasive (how much should it be noticeable/in the foreground
    c. How discriminatory (what about the exclusivity/ branding/price)

Figure A.4

Appendix B

Results of the first test

1st test



2nd and 3rd test

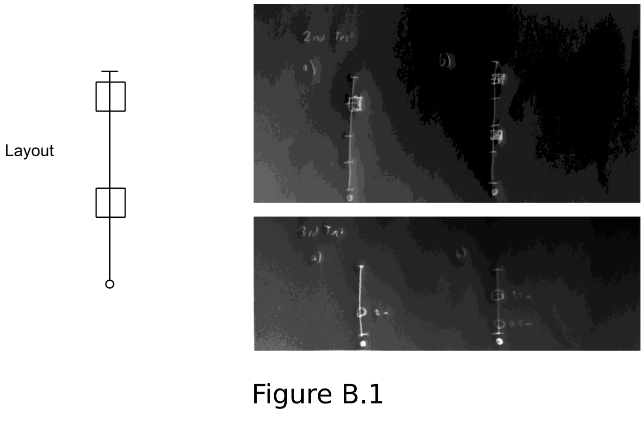
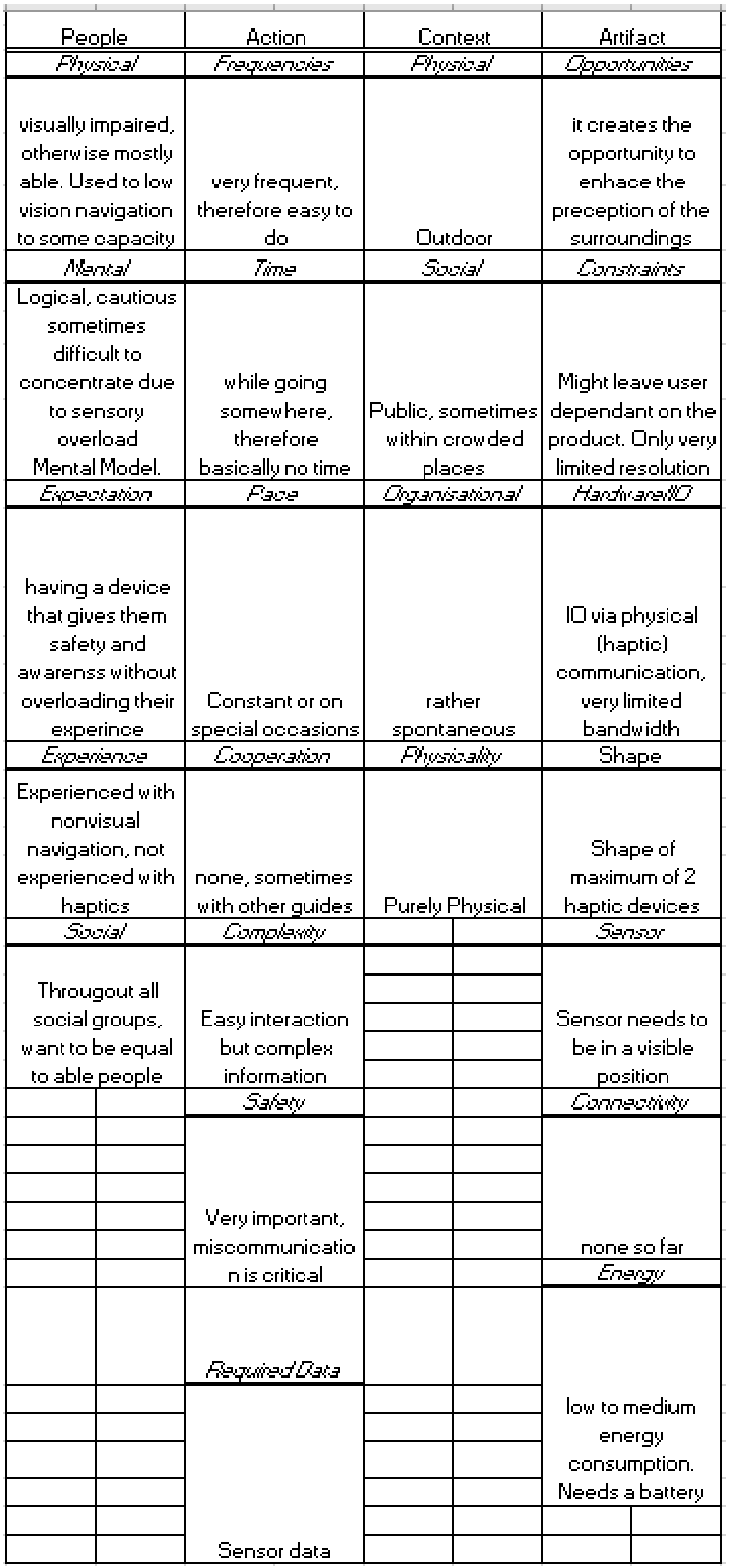


Figure B.1

Appendix C

Paca analysis

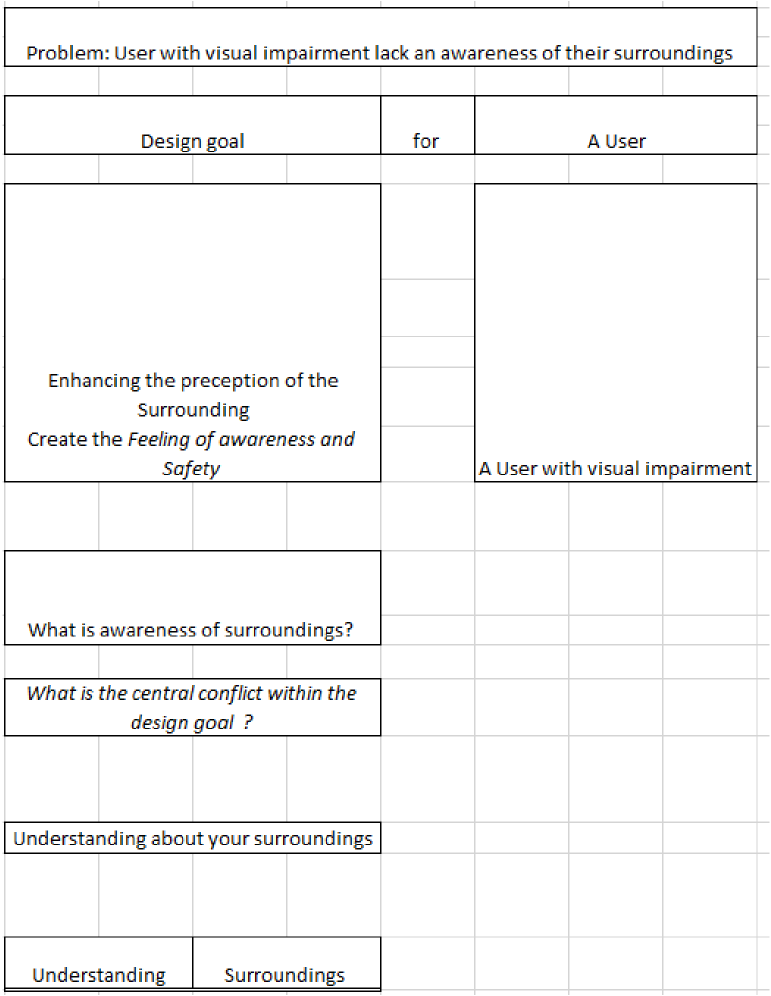


People	Action	Context	Artifact
Physical	*Frequencies*	*Physical*	*Opportunities*
visually impaired, otherwise mostly able. Used to low vision navigation to some capacity	very frequent, therefore easy to do	Outdoor	it creates the opportunity to enhace the preception of the surroundings
Mental	*Time*	*Social*	*Constraints*
Logical, cautious sometimes difficult to concentrate due to sensory overload Mental Model.	while going somewhere, therefore basically no time	Public, sometimes within crowded places	Might leave user dependant on the product. Only very limited resolution
Expectation	*Pace*	*Organisational*	*Hardware/IO*
having a device that gives them safety and awarenss without overloading their experince	Constant or on special occasions	rather spontaneous	IO via physical (haptic) communication, very limited bandwidth
Experience	*Cooperation*	*Physicality*	Shape
Experienced with nonvisual navigation, not experienced with haptics	none, sometimes with other guides	Purely Physical	Shape of maximum of 2 haptic devices
Social	*Complexity*		*Sensor*
Througout all social groups, want to be equal to able people	Easy interaction but complex information		Sensor needs to be in a visible position
	Safety		*Connectivity*
	Very important, miscommunication is critical		none so far
	Required Data		*Energy*
	Sensor data		low to medium energy consumption. Needs a battery

Figure C.1

Appendix D

Goal analysis



Problem: User with visual impairment lack an awareness of their surroundings

Design goal	for	A User
Enhancing the preception of the Surrounding Create the *Feeling of awareness and Safety*		A User with visual impairment

What is awareness of surroundings?

What is the central conflict within the design goal ?

Understanding about your surroundings

Understanding	Surroundings

Figure D.1

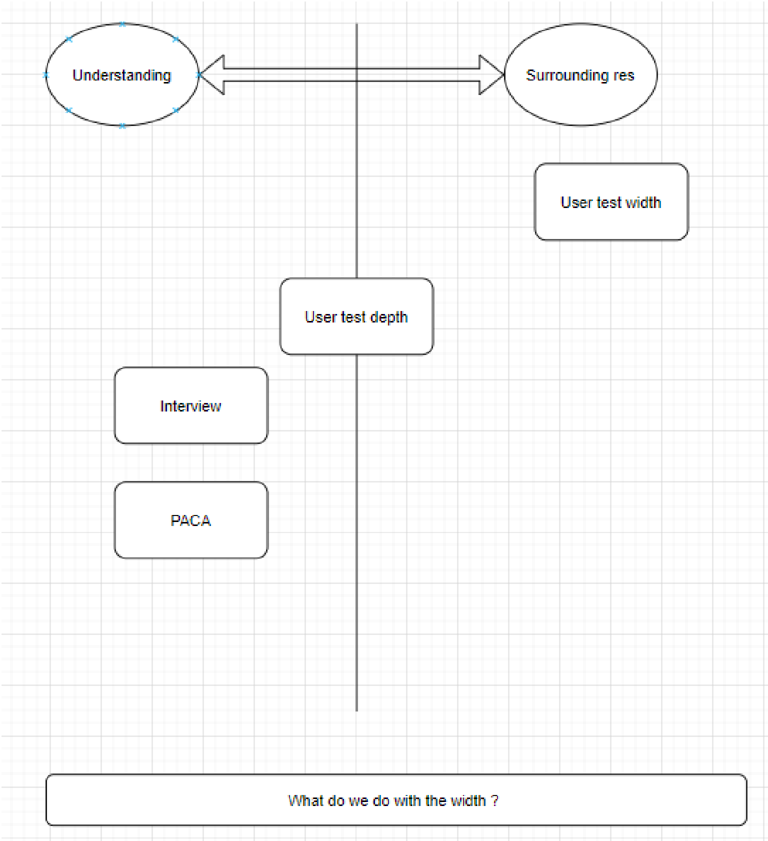
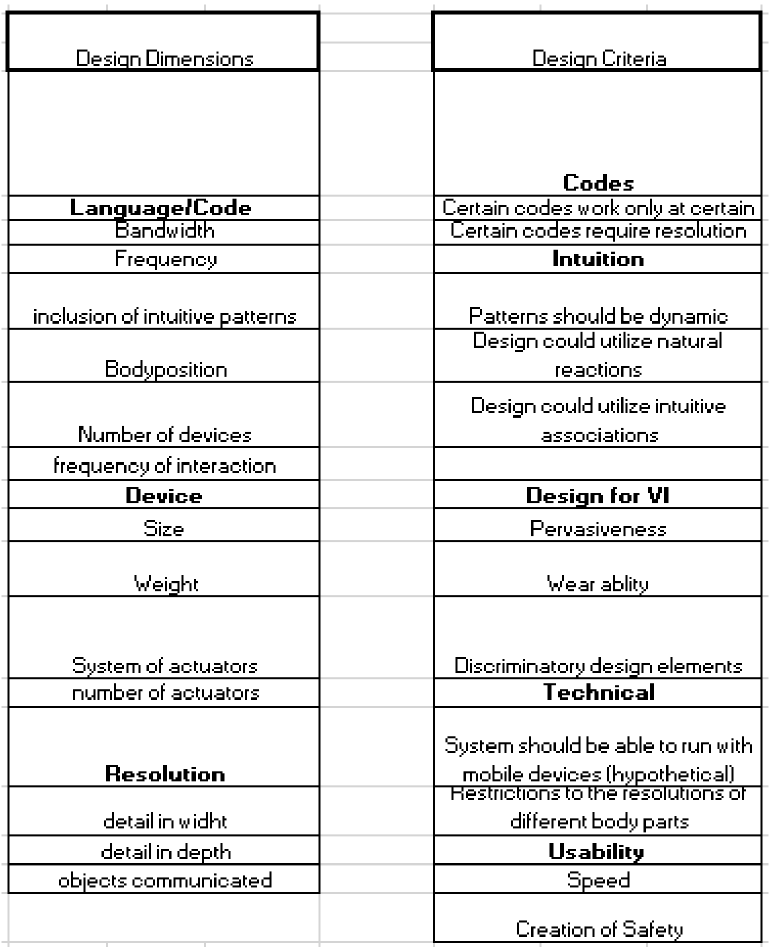

Understanding
Surrounding res
User test width
User test depth
Interview
PACA
What do we do with the width ?

Figure D.2

Appendix E

Design criteria

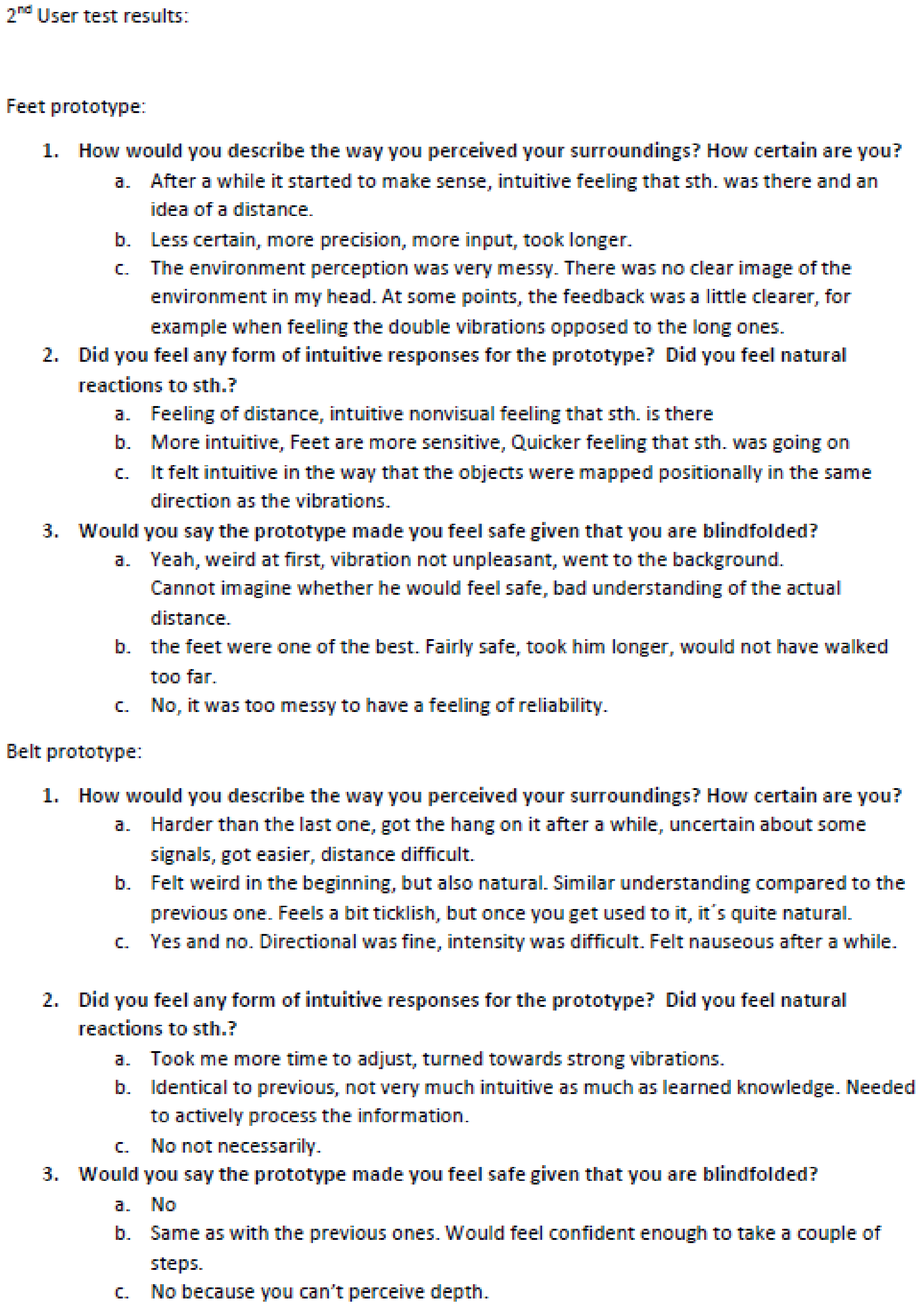


Design Dimensions	Design Criteria
	Codes
Language/Code	Certain codes work only at certain
Bandwidth	Certain codes require resolution
Frequency	**Intuition**
inclusion of intuitive patterns	Patterns should be dynamic
Bodyposition	Design could utilize natural reactions
Number of devices	Design could utilize intuitive associations
frequency of interaction	
Device	**Design for VI**
Size	Pervasiveness
Weight	Wear ablity
System of actuators	Discriminatory design elements
number of actuators	**Technical**
Resolution	System should be able to run with mobile devices (hypothetical)
detail in widht	Restrictions to the resolutions of different body parts
detail in depth	**Usability**
objects communicated	Speed
	Creation of Safety

Figure E.1

Appendix F

Results of the second test



2nd User test results:

Feet prototype:

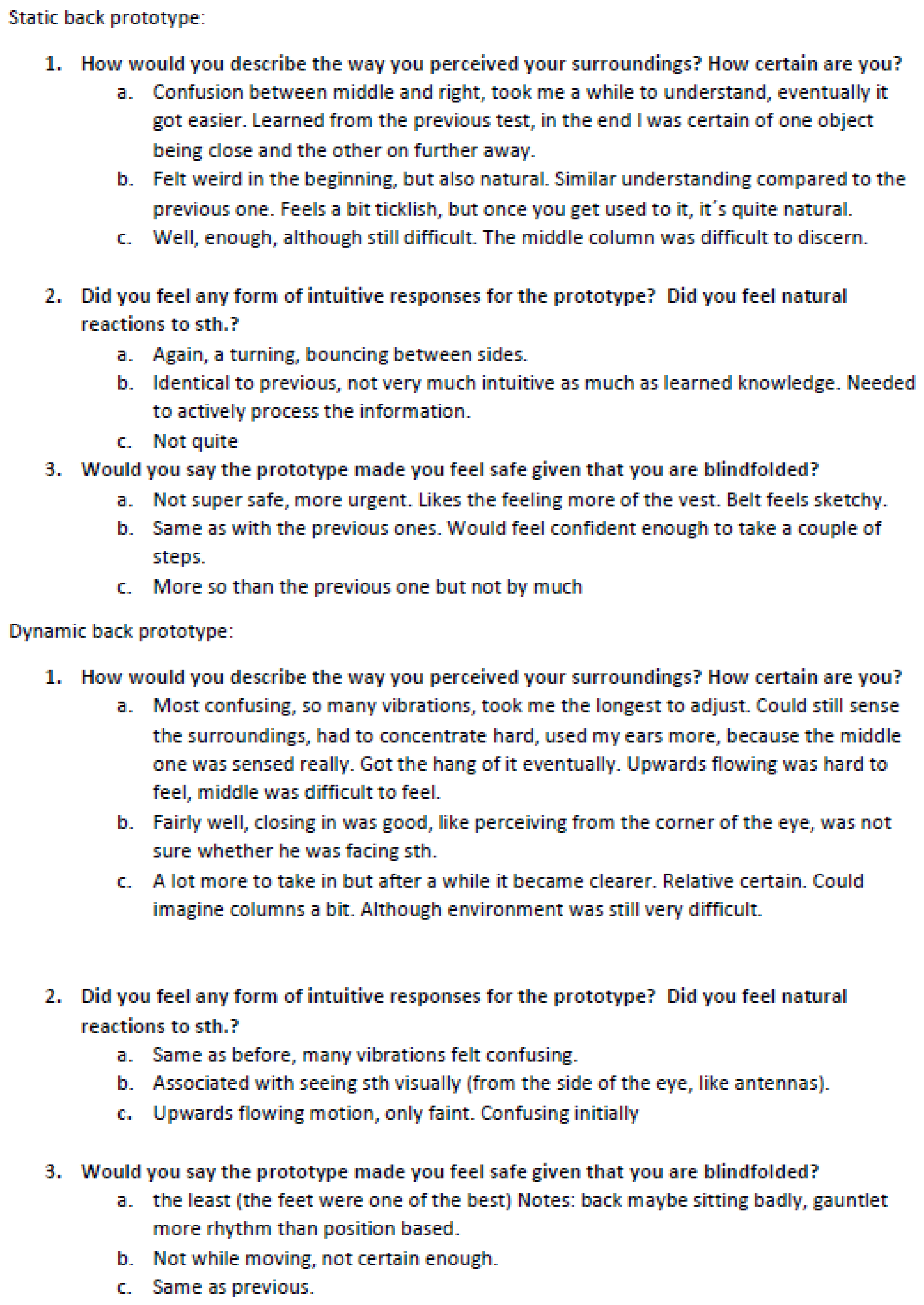
1. **How would you describe the way you perceived your surroundings? How certain are you?**
    a. After a while it started to make sense, intuitive feeling that sth. was there and an idea of a distance.
    b. Less certain, more precision, more input, took longer.
    c. The environment perception was very messy. There was no clear image of the environment in my head. At some points, the feedback was a little clearer, for example when feeling the double vibrations opposed to the long ones.
2. **Did you feel any form of intuitive responses for the prototype? Did you feel natural reactions to sth.?**
    a. Feeling of distance, intuitive nonvisual feeling that sth. is there
    b. More intuitive, Feet are more sensitive, Quicker feeling that sth. was going on
    c. It felt intuitive in the way that the objects were mapped positionally in the same direction as the vibrations.
3. **Would you say the prototype made you feel safe given that you are blindfolded?**
    a. Yeah, weird at first, vibration not unpleasant, went to the background.
    Cannot imagine whether he would feel safe, bad understanding of the actual distance.
    b. the feet were one of the best. Fairly safe, took him longer, would not have walked too far.
    c. No, it was too messy to have a feeling of reliability.

Belt prototype:

1. **How would you describe the way you perceived your surroundings? How certain are you?**
    a. Harder than the last one, got the hang on it after a while, uncertain about some signals, got easier, distance difficult.
    b. Felt weird in the beginning, but also natural. Similar understanding compared to the previous one. Feels a bit ticklish, but once you get used to it, it´s quite natural.
    c. Yes and no. Directional was fine, intensity was difficult. Felt nauseous after a while.

2. **Did you feel any form of intuitive responses for the prototype? Did you feel natural reactions to sth.?**
    a. Took me more time to adjust, turned towards strong vibrations.
    b. Identical to previous, not very much intuitive as much as learned knowledge. Needed to actively process the information.
    c. No not necessarily.
3. **Would you say the prototype made you feel safe given that you are blindfolded?**
    a. No
    b. Same as with the previous ones. Would feel confident enough to take a couple of steps.
    c. No because you can't perceive depth.

Figure F.1



Static back prototype:

1. **How would you describe the way you perceived your surroundings? How certain are you?**
    a. Confusion between middle and right, took me a while to understand, eventually it got easier. Learned from the previous test, in the end I was certain of one object being close and the other on further away.
    b. Felt weird in the beginning, but also natural. Similar understanding compared to the previous one. Feels a bit ticklish, but once you get used to it, it´s quite natural.
    c. Well, enough, although still difficult. The middle column was difficult to discern.

2. **Did you feel any form of intuitive responses for the prototype? Did you feel natural reactions to sth.?**
    a. Again, a turning, bouncing between sides.
    b. Identical to previous, not very much intuitive as much as learned knowledge. Needed to actively process the information.
    c. Not quite
3. **Would you say the prototype made you feel safe given that you are blindfolded?**
    a. Not super safe, more urgent. Likes the feeling more of the vest. Belt feels sketchy.
    b. Same as with the previous ones. Would feel confident enough to take a couple of steps.
    c. More so than the previous one but not by much

Dynamic back prototype:

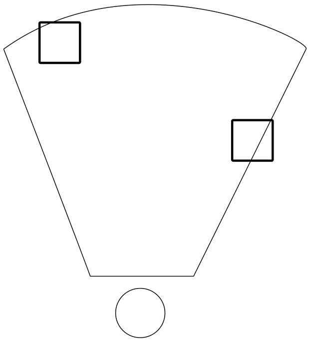
1. **How would you describe the way you perceived your surroundings? How certain are you?**
    a. Most confusing, so many vibrations, took me the longest to adjust. Could still sense the surroundings, had to concentrate hard, used my ears more, because the middle one was sensed really. Got the hang of it eventually. Upwards flowing was hard to feel, middle was difficult to feel.
    b. Fairly well, closing in was good, like perceiving from the corner of the eye, was not sure whether he was facing sth.
    c. A lot more to take in but after a while it became clearer. Relative certain. Could imagine columns a bit. Although environment was still very difficult.

2. **Did you feel any form of intuitive responses for the prototype? Did you feel natural reactions to sth.?**
    a. Same as before, many vibrations felt confusing.
    b. Associated with seeing sth visually (from the side of the eye, like antennas).
    c. Upwards flowing motion, only faint. Confusing initially

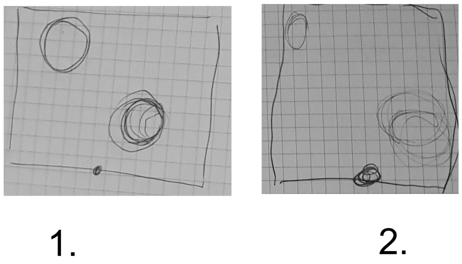
3. **Would you say the prototype made you feel safe given that you are blindfolded?**
    a. the least (the feet were one of the best) Notes: back maybe sitting badly, gauntlet more rhythm than position based.
    b. Not while moving, not certain enough.
    c. Same as previous.

Figure F.2

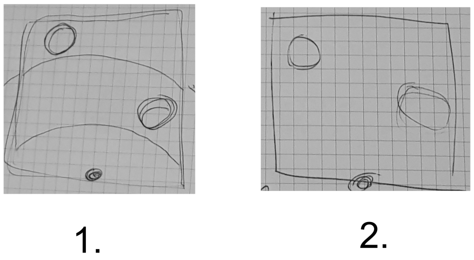
Layout



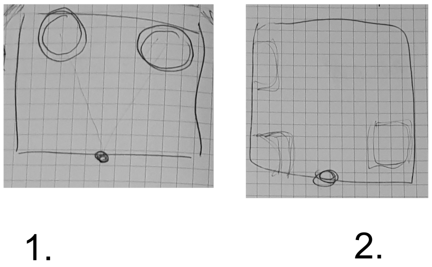
Static back prototype



Belt prototype



Dynamic back prototype



Foot prototoype

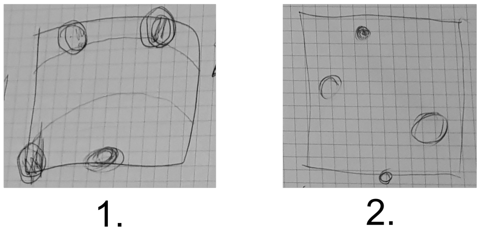


Figure F.3

Appendix G

Circuit diagram

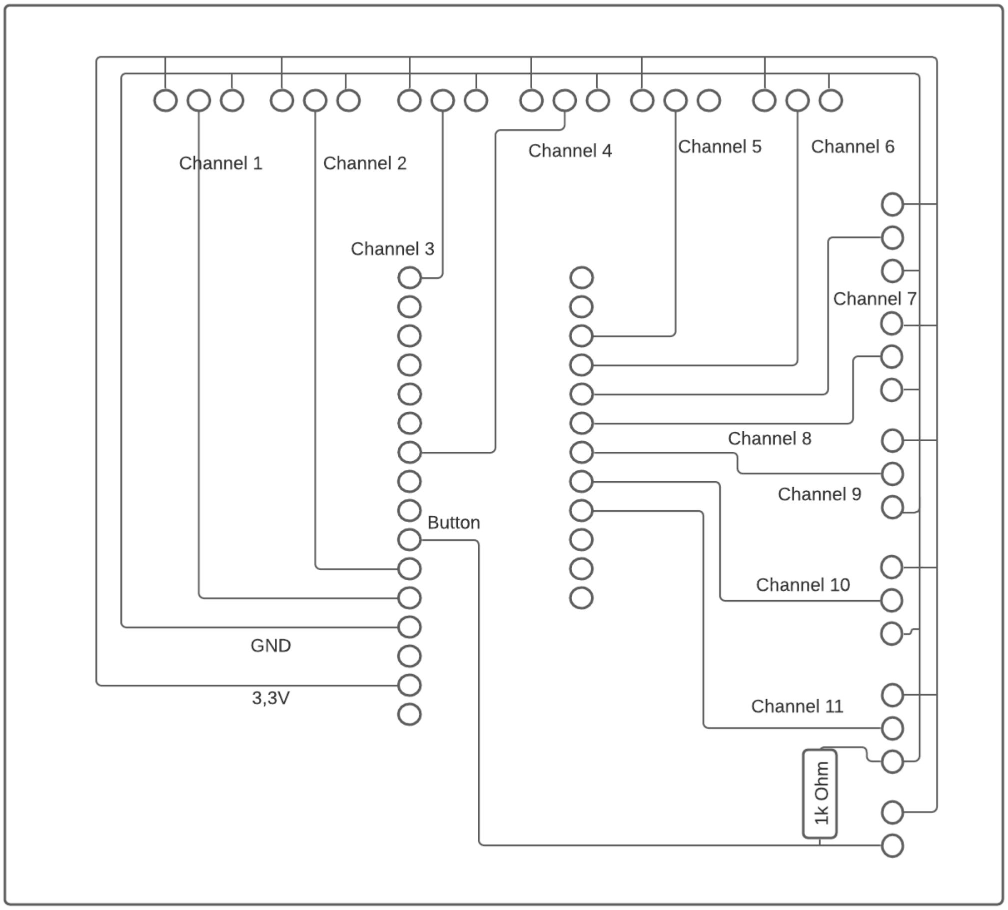
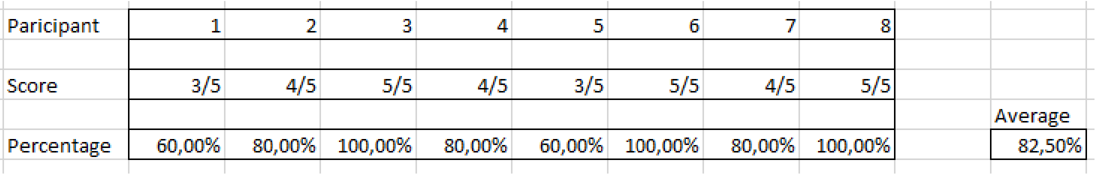


Figure G.1

Appendix H

Results of the third test

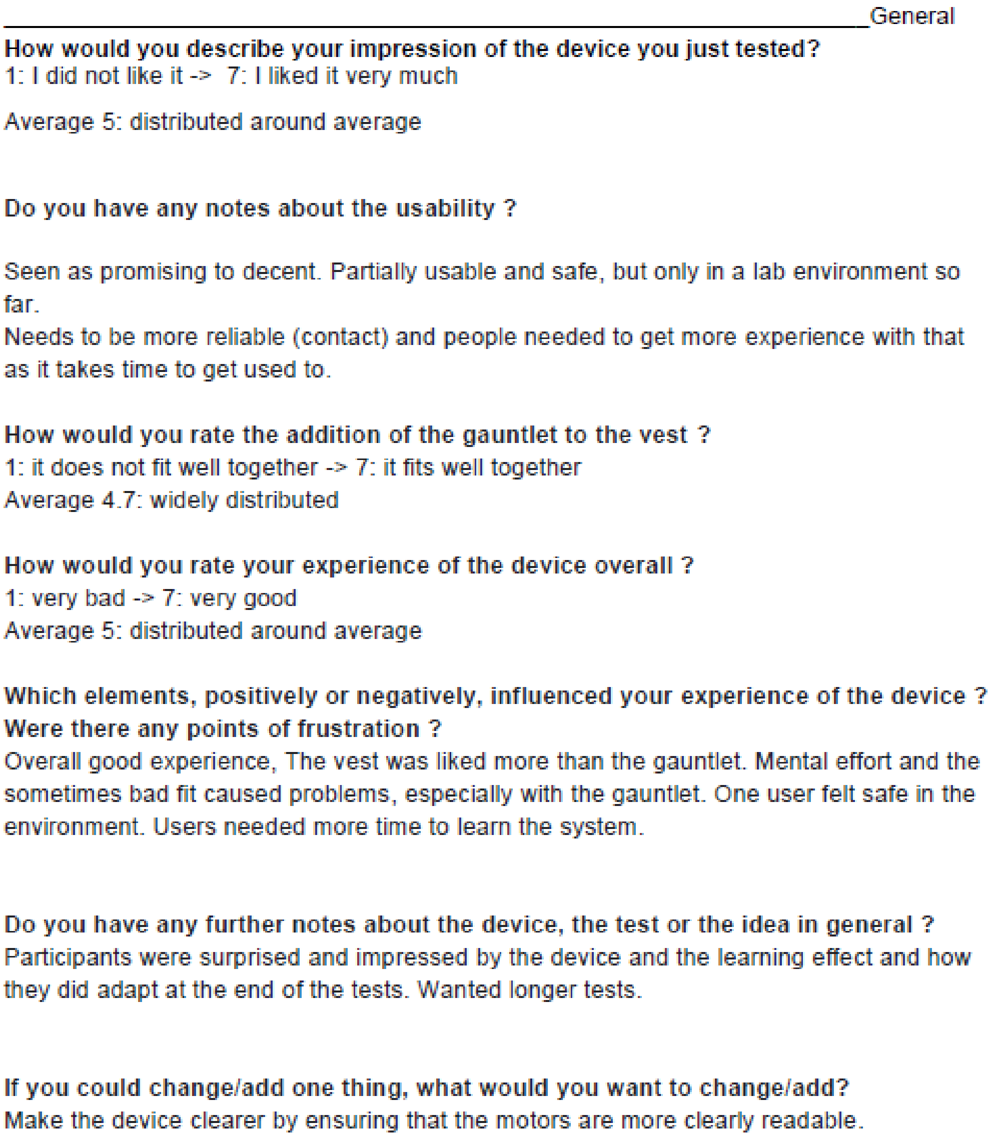


Paricipant	1	2	3	4	5	6	7	8		
Score	3/5	4/5	5/5	4/5	3/5	5/5	4/5	5/5		
										Average
Percentage	60,00%	80,00%	100,00%	80,00%	60,00%	100,00%	80,00%	100,00%		82,50%

Figure H.1

Appendix I

Results of the final test



General

How would you describe your impression of the device you just tested?
1: I did not like it -> 7: I liked it very much

Average 5: distributed around average

Do you have any notes about the usability ?

Seen as promising to decent. Partially usable and safe, but only in a lab environment so far.
Needs to be more reliable (contact) and people needed to get more experience with that as it takes time to get used to.

How would you rate the addition of the gauntlet to the vest ?
1: it does not fit well together -> 7: it fits well together
Average 4.7: widely distributed

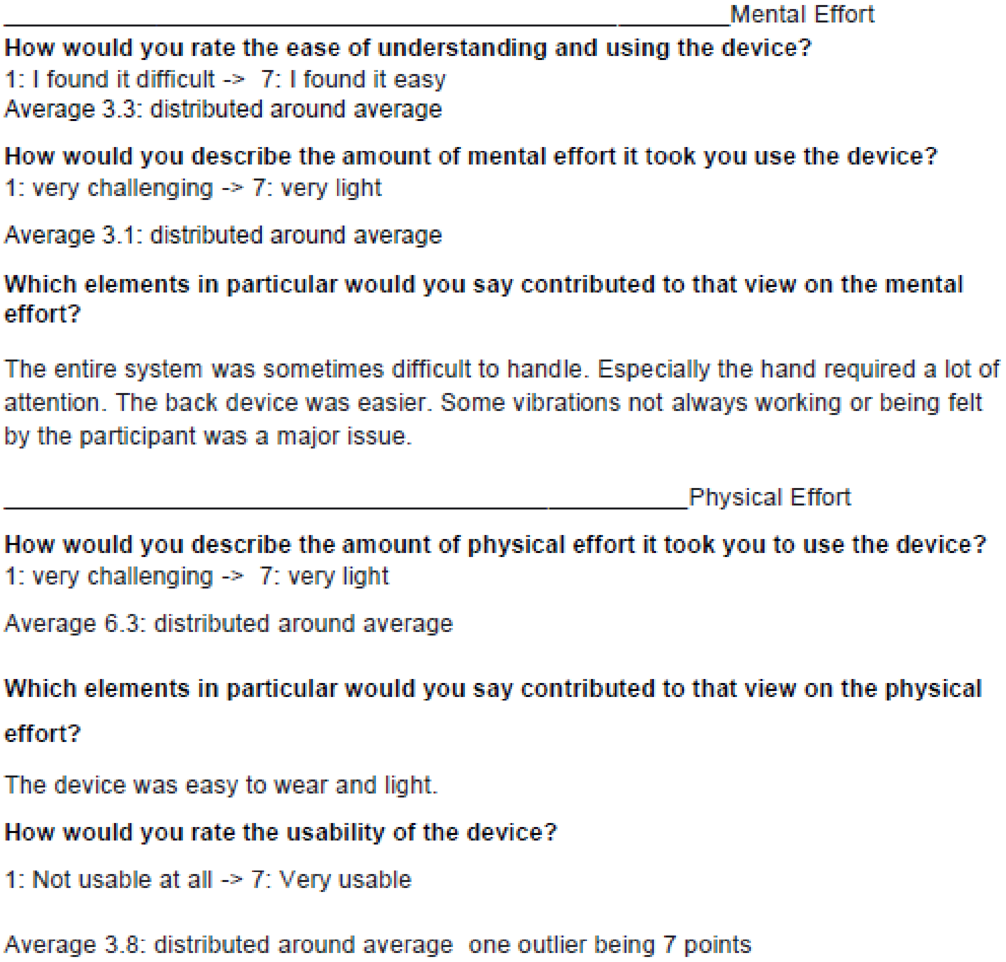
How would you rate your experience of the device overall ?
1: very bad -> 7: very good
Average 5: distributed around average

Which elements, positively or negatively, influenced your experience of the device ? Were there any points of frustration ?
Overall good experience, The vest was liked more than the gauntlet. Mental effort and the sometimes bad fit caused problems, especially with the gauntlet. One user felt safe in the environment. Users needed more time to learn the system.

Do you have any further notes about the device, the test or the idea in general ?
Participants were surprised and impressed by the device and the learning effect and how they did adapt at the end of the tests. Wanted longer tests.

If you could change/add one thing, what would you want to change/add?
Make the device clearer by ensuring that the motors are more clearly readable.

Figure I.1



Mental Effort

How would you rate the ease of understanding and using the device?
1: I found it difficult -> 7: I found it easy
Average 3.3: distributed around average

How would you describe the amount of mental effort it took you use the device?
1: very challenging -> 7: very light

Average 3.1: distributed around average

Which elements in particular would you say contributed to that view on the mental effort?

The entire system was sometimes difficult to handle. Especially the hand required a lot of attention. The back device was easier. Some vibrations not always working or being felt by the participant was a major issue.

Physical Effort

How would you describe the amount of physical effort it took you to use the device?
1: very challenging -> 7: very light

Average 6.3: distributed around average

Which elements in particular would you say contributed to that view on the physical effort?

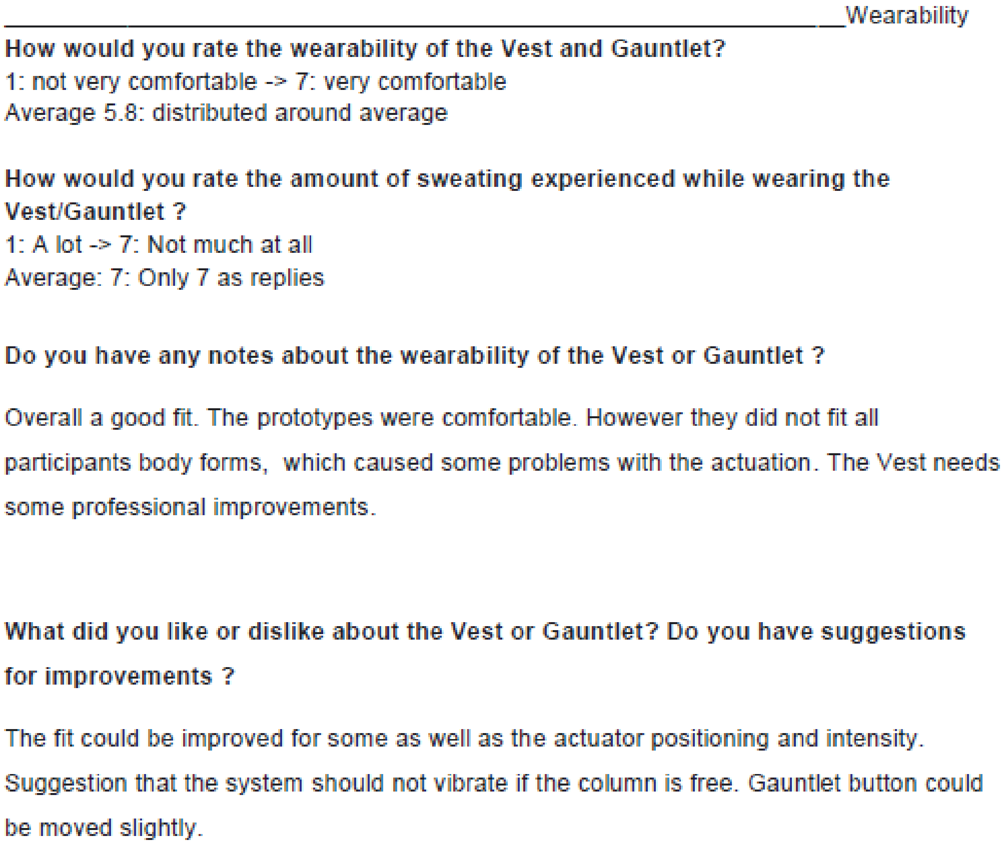
The device was easy to wear and light.

How would you rate the usability of the device?

1: Not usable at all -> 7: Very usable

Average 3.8: distributed around average one outlier being 7 points

Figure I.2



Wearability

How would you rate the wearability of the Vest and Gauntlet?
1: not very comfortable -> 7: very comfortable
Average 5.8: distributed around average

How would you rate the amount of sweating experienced while wearing the Vest/Gauntlet ?
1: A lot -> 7: Not much at all
Average: 7: Only 7 as replies

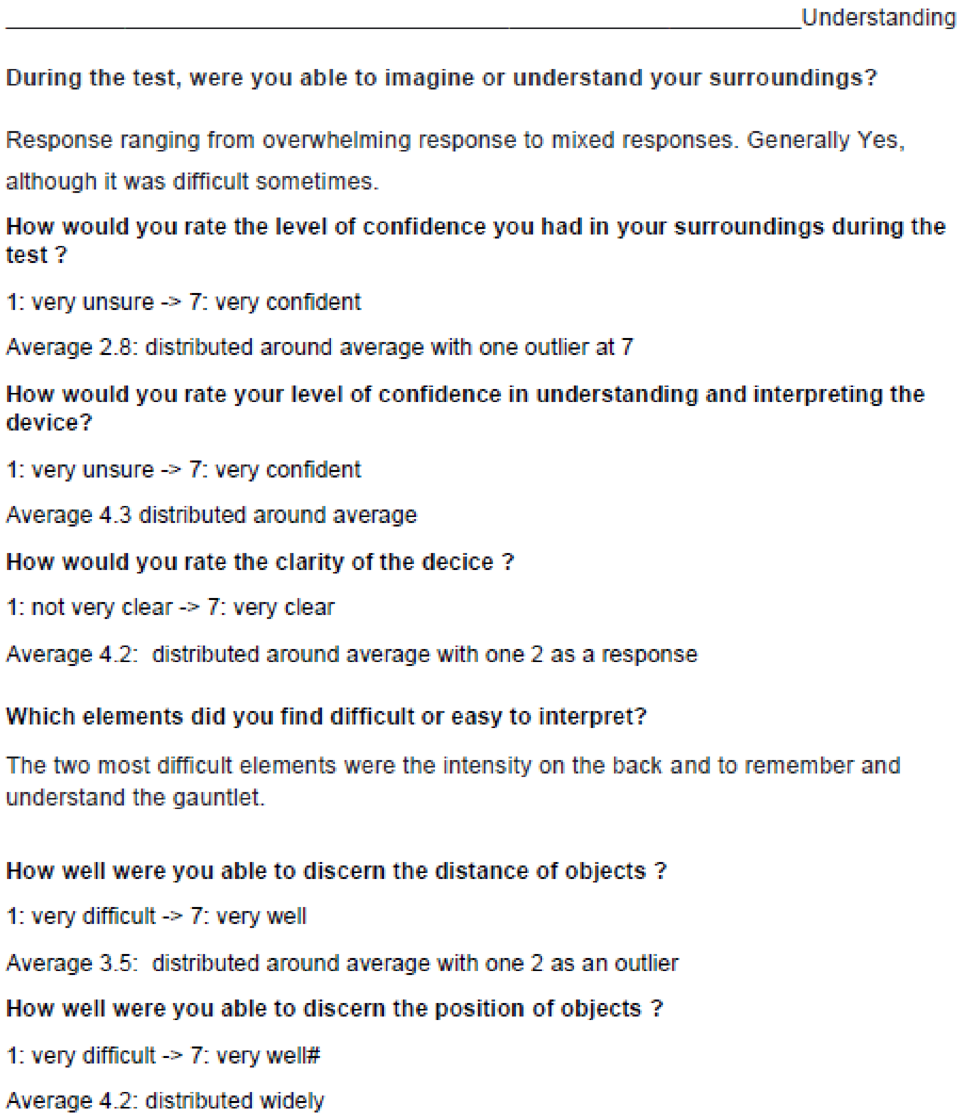
Do you have any notes about the wearability of the Vest or Gauntlet ?

Overall a good fit. The prototypes were comfortable. However they did not fit all participants body forms, which caused some problems with the actuation. The Vest needs some professional improvements.

What did you like or dislike about the Vest or Gauntlet? Do you have suggestions for improvements ?

The fit could be improved for some as well as the actuator positioning and intensity. Suggestion that the system should not vibrate if the column is free. Gauntlet button could be moved slightly.

Figure I.3



Understanding

During the test, were you able to imagine or understand your surroundings?

Response ranging from overwhelming response to mixed responses. Generally Yes, although it was difficult sometimes.

How would you rate the level of confidence you had in your surroundings during the test ?

1: very unsure -> 7: very confident

Average 2.8: distributed around average with one outlier at 7

How would you rate your level of confidence in understanding and interpreting the device?

1: very unsure -> 7: very confident

Average 4.3 distributed around average

How would you rate the clarity of the decice ?

1: not very clear -> 7: very clear

Average 4.2: distributed around average with one 2 as a response

Which elements did you find difficult or easy to interpret?

The two most difficult elements were the intensity on the back and to remember and understand the gauntlet.

How well were you able to discern the distance of objects ?

1: very difficult -> 7: very well

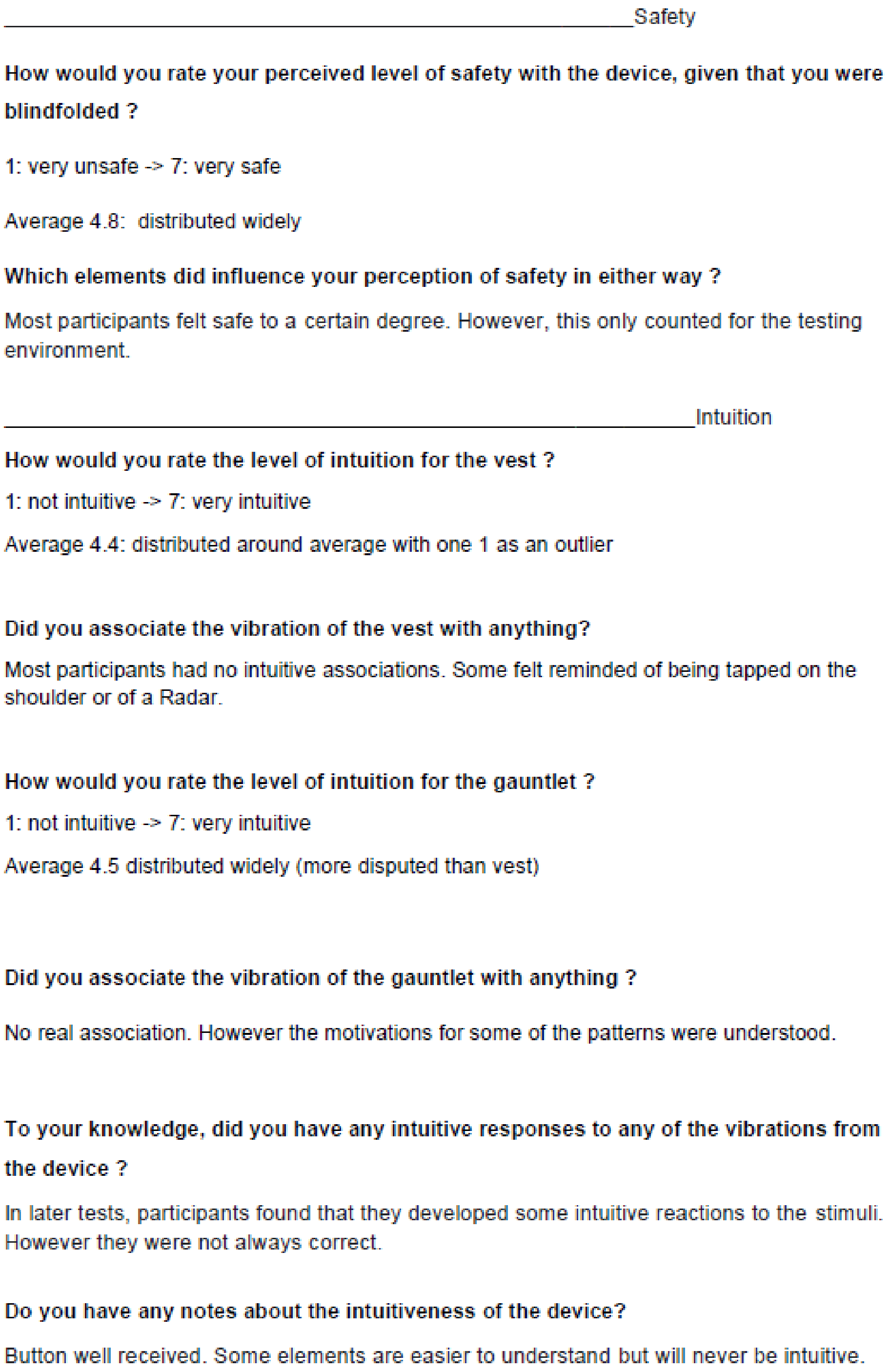
Average 3.5: distributed around average with one 2 as an outlier

How well were you able to discern the position of objects ?

1: very difficult -> 7: very well#

Average 4.2: distributed widely

Figure I.4



Safety

How would you rate your perceived level of safety with the device, given that you were blindfolded ?

1: very unsafe -> 7: very safe

Average 4.8: distributed widely

Which elements did influence your perception of safety in either way ?

Most participants felt safe to a certain degree. However, this only counted for the testing environment.

Intuition

How would you rate the level of intuition for the vest ?

1: not intuitive -> 7: very intuitive

Average 4.4: distributed around average with one 1 as an outlier

Did you associate the vibration of the vest with anything?

Most participants had no intuitive associations. Some felt reminded of being tapped on the shoulder or of a Radar.

How would you rate the level of intuition for the gauntlet ?

1: not intuitive -> 7: very intuitive

Average 4.5 distributed widely (more disputed than vest)

Did you associate the vibration of the gauntlet with anything ?

No real association. However the motivations for some of the patterns were understood.

To your knowledge, did you have any intuitive responses to any of the vibrations from the device ?

In later tests, participants found that they developed some intuitive reactions to the stimuli. However they were not always correct.

Do you have any notes about the intuitiveness of the device?

Button well received. Some elements are easier to understand but will never be intuitive.

Figure I.5