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Digital Navigational Aids for the Visually Impaired

A Designer’s Guide for Implementing Effective Feedback Solutions

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Abstract

Mobility and navigation in outdoor environments constitute a formidable daily challenge for the blind and visually impaired community. Difficulty in outdoor mobility limits participation in social activities and employment opportunities which in turn contributes to isolation and a decreased sense of mental well-being. To address these challenges, digital navigational aids (NAVIs) extend the capabilities of traditional mobility aids such as guide dogs and the white cane. However, adoption of these new technologies within the blind and visually impaired community has been low. This low adoption rate suggests that a gap exists between current solutions and user needs and goals. As intermediaries between solutions and the users they serve, designers are ideally situated to bridge this gap. Thus, this research aims to provide designers new to the problem space with an understanding of the considerations that inform NAVI design.

To build a rudimentary understanding of these considerations, a literature review of individual NAVI research projects and comparative reviews of NAVIs was conducted. The interaction design requirements framework proposed by Sharp et al. (2019) was then used as an organizational tool for further defining these considerations. Requirements categories including user experience goals, usability goals, functional requirements, environmental requirements and data requirements were applied as themes in a thematic analysis of data obtained through interviews with NAVI designers and other designers of feedback systems in an effort to identify challenges, designer approaches and areas where improvements could be made to current NAVI design solutions.

Findings from expert interviews suggest that developments emerging from the rapidly evolving technological environment can be leveraged by designers for creating more user friendly and accessible solutions. For example, user familiarity with smartphone interfaces can reduce the learning curve required when adapting to a new smartphone-based NAVI thus increasing the chances of adoption into daily use. Data obtained in interviews also examines the methods by which designers improve usability, including users not only in their iterative processes but throughout the entire life cycle of a NAVI solution. Finally, expert interviews reveal new prototyping tools for designing feedback systems with wearables which streamline the prototyping process and lower the barrier of entry for designers without prior expertise in coding or electronics.

Keywords Feedback systems, mobility aids, interaction design

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Helsinki, 5 June 2023
Tomi Monahan

Symbols and abbreviations

Abbreviations

NAVI	Navigational Aid for the Visually Impaired
BVI	Blind and Visually Impaired
VI	Visually Impaired

1 Introduction

According to the World Health Organization (2022) an estimated 2.2 billion people suffer from a near or distance vision impairment. Within this figure, 285 million are considered to be visually impaired while 39 million are classified as blind. On a global scale, lower employment among the blind and visually impaired amounts to a $411 billion annual loss in productivity. French (2017) notes that in the US, only 44% of working-aged blind or visually impaired individuals are employed as compared with the 79% employment rate among the sighted. Addressing these comparatively lower employment levels Marques et al (2021) propose the implementation of accessible and inclusive environments to increase work retention and employment opportunities for the blind and visually impaired. Accessible and inclusive solutions in this case apply to indoor, controlled environments but do not necessarily consider the challenges posed by the journey between home and work. For the blind and visually impaired, the fear of navigating a threatening and unpredictable outdoor environment can complicate regular employment and hinder regular social engagement. In the longer term, isolation from social interactions and the lack of an independent lifestyle can negatively impact health and mental well-being. Demmin et al (2020) maintains that social isolation and restricted mobility contribute to higher levels of anxiety and depression among the blind and visually Impaired. Similarly, Augestad (2017) maintains that self-esteem among blind and visually impaired children and young adults is most notably influenced by access to meaningful social interactions and the cultivation of independent mobility skills. Thus, it stands to reason that better mobility can help to reduce isolation and increase physical and mental well-being for the blind and visually impaired, providing greater access to social, cultural and employment opportunities.

Traditionally, guide dogs, the white stick and personal assistants have been used by the blind and visually impaired as mobility aids. While this remains true today, a proliferation of new digital assistive navigational aids or NAVIs, has expanded the range of options available to the blind and visually impaired (BVI) community. These new options do not in all cases seek to supplant traditional methods but rather to augment them, providing users with novel ways to sense and navigate through their surroundings. Adding to the obstacle detection afforded by the white cane, newer methods by which to describe the user's physical environment such as speech descriptions of obstacles and places of interest enhance situational awareness and add to experiential richness for the user. Haptic and audio cues used in conjunction with GPS and open-source maps also facilitate quick and independent mobility previously only achieved with the help of guide dogs or personal assistants.

Moreover, these capabilities are presently integrated within and deployable through widely used ubiquitous technologies such as smartphones and tablets. According to Payyanur (2019) in adapting to a new interface, familiarity with a preexisting format or technology reduces the user's learning curve and increases accessibility upon first use. Familiarity with ubiquitous technologies among the BVI community thus can be leveraged to reduce the learning curve for new users and to lower barriers to accessibility when adapting to new NAVIs. However, other features of presently available NAVIs do not meet user needs or expectations as evidenced by low adoption rates among the BVI community. Lloyd-Esenkaya et al. (2020) state that up to 30% of NAVIs are abandoned after initial use. This research aims to explore the reasons for these lower adoption rates. By examining the multiple requirements essential to the design of NAVIs, this research identifies shortcomings in current designs and design approaches and proposes new ways for designers to arrive at more effective solutions. The following research questions guide this exploration.

- Why are adoption rates for assistive navigational technologies low among the visually impaired?

- What are the essential requirements for designing effective assistive navigational aids for the blind and visually impaired?

- How can these requirements be further defined to help designers of assistive technologies arrive at more effective feedback systems?

According to Privitera (2015) design requirements can be defined as a set of initial goals and desired functionalities discovered or captured in the early phases of the design process helping designers to develop features which best reflect user needs. Sharp et al (2019) proposes the use of a set of requirement categories which help to further define these desired functionalities upon approaching a new design problem. These include, functional requirements, data requirements, environmental requirements, usability goals and user experience goals. In this research, these requirement categories are applied to the multiple facets involved in the design of NAVIs as a means to better understand these facets as distinct entities as well as how they interrelate. As NAVIs are primarily communicative tools used to describe aspects of the physical environment that are most relevant to the user in fulfilling the functional goal of navigation and mobility, data requirements, or more specifically feedback systems are necessarily prioritised. In this hierarchy, three separate environmental requirements can be seen to interact and express constraints that inform the design of these feedback systems. For instance, feedback systems must provide a representation of aspects of the physical environment that are useful to the user in fulfilling the desired task, yet the quality and timing of such representations are constrained by what is currently possible within the context of technologies existing in the technical environment. Additionally, feedback systems are constrained by the ways in which the human mind receives and processes external stimuli. In a busy physical environment for example, feedback may need to be deployed sparingly so as not to overload the user's senses. Thus, to properly address constraints related to human perception, this research introduces the category, internal environmental requirements, to capture physiological and neurocognitive considerations that influence the design of feedback systems. A feedback system that fails to align physical, technical and internal environmental requirements in fulfilling functional requirements can in turn negatively impact usability goals and user experience goals. Sharp et al (2019) describe usability goals and user experience goals as attributes of an interface that support or facilitate the user's integration of a device or service into daily use. In the context of NAVIs, usability goals refer more specifically to the ease by which an interface is learned and how customisable or moldable that interface is to user needs while user experience goals describe cost, size, portability and appearance factors. Designers must ultimately consider how a design solution meets these usability and user experience goals in achieving higher adoption rates among the BVI user group.

In this research, to gain an understanding of the requirements essential to NAVI design, two categories of literature are examined. Reviews of a selection of NAVIs offer comparative perspectives which feature recommendations for future improvements in design, while literature describing individual NAVI projects offers a more detailed glimpse into feedback systems, technical choices and even the testing and prototyping processes. Reviews highlight either the technical or the internal environments. For example, Kristjansson et al. (2016) discusses the constraints imposed upon NAVI design by the way in which humans process external sensory stimuli and introduces guidelines for the design of NAVI feedback systems. Kuriakose et al. (2020) and Messaoudi et al. (2022) in turn, in conducting comprehensive reviews of current NAVIs, offer a more technical perspective on NAVI design. In exploring data requirements, or specific NAVI feedback systems, literature featuring individual NAVI projects provides useful insights. Ton et al. (2018) describe the use of spatialized sound to convey an object's distance, angular orientation and height while Nevin (2022) detail a multimodal feedback system featuring descriptive speech and audio cues. Novich et al. (2015) describe optimising haptic feedback for better recognition and differentiation of signals by users and faster transmission. Moesgen et al. (2022) applies repulsive and attractive haptic feedback to guide bodily movements.

The role played by the complexity of a feedback system in relation to the required training time and how this affects usability goals is also examined in the literature. While Kristjansson et al. (2016) support extensive training as a means to achieve externalization or a sense of realness when interacting with the physical environment through a NAVI interface, Kuriakose et al. (2020) suggest that a reduction in training times is more conducive to user acceptance. Traditional sensory substitution feedback methods tend towards complexity and require longer training regimens. This is because sensory substitution aims to gradually retrain the neural pathways of the user's brain to repurpose cortical regions to process nonvisual feedback as if it were actual vision. Toth & Parkkonen (2019) describe the application of a visual to audio sensory substitution device. However, in training to use this device, the training time required is not commensurate with functional benefits afforded. A different strategy is proposed by Aiordachioae et al. (2020) when noting that currently available computer vision algorithms and deep learning methods support the provision of dynamic situational awareness through multimodal descriptive and haptic feedback. Such approaches to designing feedback require considerably reduce the training time needed by users when adapting to a new NAVI.

When applying a requirements framework to better define the NAVI problem space, it is important to acknowledge that certain trends and phenomenon may not be fully captured by this framework alone. For the purpose of capturing phenomenon that will impact the future design of NAVIs, this research explores developments and trends of more recent import. While these exist mainly within the technical environment, they represent fundamental and even revolutionary shifts in the way technologies can be leveraged for better design. These include the widespread use of ubiquitous technologies and the integrated technologies and capabilities they provide, AI descriptive technologies, neural networks, computer vision and the gradual miniaturisation of components like microprocessors, actuators and sensors. As previously mentioned, ubiquitous technologies provide a familiar format already in widespread use. NAVIs introduced through this format are more accessible to users by virtue of this familiarity and thus the barrier to user adoption is lowered. Swobodzinski et al. (2019) reviews such smartphone based NAVIs and conducts focus groups with BVI users to identify shortcomings in usability and user experience. AI descriptive technologies, neural networks and computer vision contribute to better feedback systems by providing more detailed representations of the physical environment that allow users to more readily map and interact with features of their surroundings. Lo Valvo et al. (2021) describe the development of a NAVI using the aforementioned technologies with descriptive speech feedback. Lock et al. (2023) envision the use of neural networks to facilitate co-adaptive and ongoing learning throughout the entire use lifecycle of a NAVI. Regarding developing technologies, Real & Araujo (2019) note that miniaturisation of components allows for the design of more discreet and portable NAVI wearables which align with user experience goals. Dos Santos et al. (2020) stress the importance of considering size and appearance in NAVI design to avoid imparting a negative social stigma to the user in public spaces. Thus, both practical and aesthetic goals are supported by the trend towards miniaturisation and the options provided by the wearables market. Findings obtained from expert interviews also reveal a trend toward democratisation of tools for the design of haptic and audio feedback systems. Bypassing the need for a background in coding and electronics, availability of such tools considerably reduces the challenges previously faced by designers when engaging with feedback design. Findings also reveal the need for a creative common to support further development of standards for feedback systems. Rudimentary guidelines for feedback systems as provided by platforms like Apple already exist. Further development of guidelines, through such widely used platforms provide an ideal channel through which to reach the greater populace.

In addition to developments and trends and falling outside of the requirements framework used here, design strategies relevant to NAVI design are also examined. These include, inclusive design and scale, testing, exploration, prototyping and cross disciplinary collaboration. Lloyd-Esenkaya et al. (2020) promote scaling the navigational benefits that NAVIs provide to the niche BVI community to a wider target user group to maximise these benefits for all and to diversify feedback options and versatility in the general technical environment. Findings from this research echo this strategic approach while noting that the gateway for development of more widely applicable navigational technologies is often entered by first working with the BVI community. In NAVI design, testing exploration and prototyping overlap and are fundamental to the iterative design process providing designers with valuable information for improving and fine-tuning before delivery of a solution. To align with user needs more closely, designers must acknowledge individual visual conditions as well as cultural and physiological differences related to the age of test participants. Moesgen et al. (2022) emphasise the need to test haptic feedback with users as age and neurological differences impact the way in which feedback is perceived. In a review of NAVI research projects, Parker et al. (2021) note that only 33 of the 35 projects reviewed mention the specific etiologies of test participants and, thus, fail to take into account the heterogeneity of the BVI community when testing. Interview participants describe cross disciplinary collaboration as an integral part of the NAVI design process. Designers cannot be expected to fulfil all roles in the development of NAVIs. Therefore, outsourcing or consulting with experts is at times necessary. This is particularly relevant when technical or medical expertise is applicable.

In summation, this thesis begins with a literature review which provides an exploration into the intricacies of NAVI design. Topics that emerge as patterns within the literature examined contribute to the formulation of questions that help to further define what designers must consider when engaging in NAVI design. These questions, used in expert interviews, help this research to arrive at data which confirms what has been explored through literature review, to expand upon that data and to discover that which has not been addressed and might benefit designers of NAVIs in their future design process. Braun & Clarke (2006) state that thematic analysis is well suited for the identification of patterns within a given dataset. Therefore, this research uses the method of thematic analysis in processing data obtained from expert interviews. In organizing the data into themes that can later be more readily used by designers, this research applies the requirements framework as described by Sharp et al (2019) adding the themes of trends and design approaches to capture phenomena inadequately addressed in the examined literature.

Findings from the data thus processed suggest that developments emerging from the rapidly changing technical environment are ideally suited to provide designers with tools for more effectively aligning NAVI feedback solutions with neuro cognitive considerations. These developments also support better representations of the physical environment. In addition, trends such as miniaturization of technologies and the widespread adoption of ubiquitous technologies contribute to improved user experience and usability. Designers leveraging these trends into new NAVI designs are now able to create less socially stigmatizing, more portable and cost-effective solutions for users while using the familiarity provided by widespread smartphone and tablet use to enhance user accessibility. Finally, new platforms for designing and prototyping feedback systems lower the barrier of entry for designers hitherto thwarted by insufficient skills in coding and electronics.

2 Literature review

2.1 Identifying Requirements in the Literature on NAVI Design

Interaction Design, a subcategory of UX Design examines the relationship between potential product or service and the user it intends to serve (Kolko, 2011). Sharp et al. (2019) describe four activities deployed in the practice of Interaction Design which roughly correspond to the discover, define, develop and deliver phases of the Double Diamond framework proposed by the Design Council in 2004 (Person, 2022). These include discovering requirements, designing alternatives, prototyping and evaluating. In this research, we will apply the first of these activities, discovering requirements, to a review of relevant literature in order to portray a more wholistic view of the challenges inherent to the design of navigational aids for the blind and visually impaired.

Requirements help define how a product or service will perform. In Sharp et al. (2019) six specific requirements are discussed. These include functional requirements, data requirements, environmental requirements, user characteristics, usability goals and user experience goals. Functional requirements describe the tasks the product is intended to perform. Data requirements describe the information that will be communicated within or through the prduct. Environmental requirements include the physical surroundings in which the product will be used but can also refer to social or technical environments that inform the design of a product. User characteristics relate to the specific user group which the product is intended to serve. Usability goals describe how accessible the new product is for the user and user experience goals are related to trust, safety, comfort and aesthetic concerns. According to Sharp et al. (2019) capturing requirements in the earlier phases of the design process allows for user needs to be considered throughout the iterative cycle while communicating more effective guidelines to developers for reaching product performance goals.

NAVI design presents a complex environment in which solutions often fall short of performance goals and user expectations (Messaoudi, 2022). Designers approaching the NAVI problem space for the first time must contend with a myriad of diverse and sometimes conflicting information about what constitutes an effective design solution. Therefore, to present a more comprehensive analysis of this environment, one that might help designers to streamline the NAVI design process, this research aims to discover requirements as they emerge in the literature. As requirements in NAVIs do not exist as fully independent entities, their interdependencies will also be examined.

To achieve these aims two main categories of literature about NAVIs will be explored. The first category provides a comparative overview of existing NAVIs through which a set of generalized shortcomings or challenges can be more readily identified. Literature in the second category proposes or details the development process of a single NAVI project. While the former exhibits trends and patterns shared by multiple projects that persist across a longer time frame, the latter offers more immediate insights into the practicalities of NAVI design. Insights gained from these complimentary streams of literature will be applied when examining discovered requirements. Additionally supplementary literature detailing technical, social or neurocognitive considerations will be used to further define these requirements. Finally, the reasons for low adoption rates of NAVIs by the visually impaired will be explored. This exploration will help to reveal usability and user experience concerns to be addressed in future NAVI designs.

According to Sharp et al. (2019) all interactive products incorporate some form of data. As NAVIs are meant to serve the user in navigating through dynamic surroundings, it is important to consider the type and accuracy of the data that will be conveyed. In the context of capturing requirements essential to effective NAVI design, data requirements can be prioritized as a hub around which all other requirements are gathered. Data, in this case, the feedback language communicated through a NAVI, serves as the primary link between the user and performance goals on one hand, and the physical environment on the other. However, the characteristics and constraints presented by the neurocognitive or internal environment are no less important when considering data requirements as the ability of the user to effectively process data about the physical environment is determined in large part by this internal or neurocognitive environment. Kristjánsson et al. (2016) suggest that while sophisticated NAVI feedback methods have been developed, research into how tactile and audio signals are interpreted by the central nervous system and which types of feedback are most effective for conveying information to particular senses has not been adequately researched. This call for additional neurocognitive research into feedback methods reveals an incomplete understanding with regards to more precise aspects of constructing feedback languages. This is reflected in the diversity of feedback methods deployed by NAVIs today. Nevertheless, a more generalized set of concepts and understandings, emerging from the cognitive sciences have hitherto guided the design of NAVI feedback methods.

2.2 Cognitive Science as a Starting Point for NAVI Feedback Methods

Visually impaired and blind people suffer from a partial or complete loss of the faculty of vision. NAVIs therefore strive to remedy this deficit by replacing visual information with auditory and/or haptic substitutes. The feedback languages that emerge from such cross-modal translations draw from understandings and ongoing research in the cognitive sciences. Neuroplasticity theory describes the ability of the central nervous system to rewire itself in response to novel stimuli. According to Real et al. (2019) the abandonment of a static conception of the brain in favor of the more flexible model promoted in this theory serves as the basis for the concept of sensory substitution, or the capability of the central nervous system to process information belonging to one sensory modality through another. In simple terms, this capability can be demonstrated by the preexistence of cross modal correspondences such as the seemingly arbitrary association of lemons with speed or boulders with sourness. Lloyd-Esenkaya et al. (2020) state that sensory substitution methods make use of these preexisting cross modal correspondences by eliciting mental images through alternative sensory channels. Ward & Meijer (2010) determined through observation that long term users of the vOICe, a visual to auditory sensory substitution device, had developed a form of synthetic synesthesia whereby auditory stimuli evoked visual cognitive forms. This phenomenon is equally relevant for visual to haptic cross modal translations. Ojala (2018) states that over time, the central nervous system can learn to process visual information through the sense of touch. Lloyd-Esenkaya et al. (2020) clarify the mechanism for cross modal generalization, or the sharing and integration of sensory data between cortical regions corresponding to different sensory inputs by introducing the concept of the meta modal organization of the brain. In this concept the operations of the brain are organized by functional or computational tasks rather than by sensory modality. Proulx et al. (2014) add to this concept, stating that the complexity of a given task significantly influences cross modal generalization. In clearer terms, complex activities introducing novel stimuli through one sensory channel tend to engage cortical regions attributed to other senses. According to Lloyd-Esenkaya et al. (2020) in an effort to achieve spatiotemporal congruence, the brain interprets, integrates and combines data gathered from one or multiple sensory channels. This spatiotemporal congruence enhances the perceiver's perception of what is real. Sensory substitution devices have sought to achieve this sense of realness through consistent training regimens allowing time for the linkages between different cortical regions to be reinforced. Kristjánsson et al. (2016) adds that through long term active engagement with a sensory substitution device, externalization, or the perception of realness attributed to external objects as communicated through an artificial feedback method is significantly enhanced.

Hebb's statement, "Neurons that fire together, wire together." (Hebb, 1949) epitomizes the adaptive potential of the human brain as described by neuroplasticity theory. However, the sensory substitution solutions inspired by this theory have not in all cases been successful at aligning with user goals and practical concerns. Earlier sensory substitution-based NAVI solutions sought to replicate the data contained within the visual domain without considering the speed at which this data needs to be received and processed in order to be useful to the user in achieving functional goals. The vOICe sensory substitution device, as described by Ward & Meijer (2010) presents a translation of the user's immediate indoor surroundings through a soundscape which plays out over the course of several seconds. In a dynamic outdoor setting however, this feedback strategy is rendered ineffective in communicating the immediacy of moving objects and obstacles. In this case, the user experience afforded by the NAVI device, if characterized by a perception of feeling unsafe, will hamper the user's adoption of the device. In response to this shortcoming as displayed in previous sensory substitution methods, Kristjánsson et al. (2016) recommend that when designing for feedback systems, the way in which a given sensory channel processes spatiotemporal continuity should always be assessed. Novich & Eagleman (2015) in testing for user recognition of complex encoded haptic signals, also stress the need for information to be optimized for quick transmission.

2.3 Sensory Perception

Recommendations provided in reviews of NAVIs suggest a consensus among researchers on certain key considerations for implementing future NAVI design. In particular, when developing feedback systems, limitations imposed by sensory bandwidth must be considered. According to Kristjánsson et al. (2016), the limited information processing capabilities of sound and touch as compared with sight necessitate a frugal provision of feedback through these channels. Ahlmark (2022) relates that while a sighted individual is able to perceive environmental features at a glance, a visually impaired individual must build awareness of environmental features in steps. In terms of data to be conveyed through feedback, this awareness can be achieved through the introduction of landmarks presented at key intervals to facilitate localization and spatial awareness. As the immediacy and full range of visual information is not easily conveyed through audition or touch, a task-oriented approach is also recommended. Accordingly, Kuriakose et al. (2020) propose that NAVIs should provide only necessary information for obstacle avoidance, paying special attention to timing. Acknowledging the dynamic nature of the perceived environment, feedback methods should take into account that, "perception is a continuous process and does not involve a snapshot of the environment" (Kristjánsson et al, 2016). Thus, the challenge in designing effective feedback systems for NAVIs involves providing continuous but only relevant information in such a manner that the user is kept in the loop yet not overwhelmed.

2.4 Feedback Modalities

Feedback languages are unimodal or multimodal depending on the variety of feedback modalities provided. Feedback modalities include haptic feedback, auditory feedback and speech. A multimodal feedback language incorporates two or more of these modalities. Kristjánsson et al (2016) recommend that a feedback language incorporate multiple modalities. The rationale behind such a strategy is reflected in the statement, “humans have a limited capacity to receive, hold in working memory and cognitively process information taken from the environment, the use of only one sensory modality to convey information can quickly overload that modality.” (Velázquez, 2010, p.15) Additionally, Velázquez (2010) notes that audio feedback in particular should not interfere with perception of environmental factors. In comparing modalities, Patil et al. (2018) mentions that tactile feedback is advantageous in that it does not occlude sound from the user’s surroundings. Kuriakose et al. (2020) adds that a multimodal distribution of feedback can help prevent sensory overload while also providing users with flexibility in different environments. Thus, when constructing a NAVI feedback language, the interplay between physical and internal environmental requirements must be considered. As the literature suggests, multimodal feedback systems lend flexibility in navigating varied environments and alleviate the risk of sensory overload through overburdening a single sensory channel.

2.5 Function & Feedback Complexity

While insights from the cognitive sciences underpin NAVI design, feedback languages still vary considerably in their approach and exhibit a wide range of complexity. On the more accessible end of this range, the example of the WayBand haptic wearable described in WearWorks (2023) deploys a single actuator, which provides corrective haptic feedback in direct relation to the degree to which the user deviates from a predetermined route. In the resulting haptic corridor, no feedback is necessary while the user is on the correct path. A more involved NAVI feedback solution proposed by Lock et al. (2023) describes the use of spatialized sound where variations in pitch, gain and panning correspond to the height, horizontal distance and angular orientation of an obstacle. In contrast to the former example, the latter allows for a more direct sensing of individual objects in the user’s environment. This added level of complexity will undoubtedly increase the training time necessary to achieve user proficiency. In defense of extended training, Kristjánsson et al. (2016) argues that without it, the long-term development of distal attribution, or an enhanced spatial awareness of external objects through a given sensory substitution method is unlikely. Tóth, & Parkkonen (2019) also maintain that true sensory substitution, with its attendant synthetic synaesthesia can take months or even years of practice to attain. However, Lloyd-Esenkaya et al. (2020) note that sensory substitution methods have often come under scrutiny for failure to achieve general acceptance beyond the laboratory. In the literature, longer training requirements are linked to low adoption rates by users. Lloyd-Esenkaya et al. (2020) note that up to 30% of NAVIs are abandoned by users before they can be applied in daily use while Kuriakose et al. (2020) suggest that a reduction in required training time may contribute to greater user acceptance. To improve usability and address low adoption rates, Messaoudi et al. (2022) suggest that user interfaces should help users to learn how to operate a NAVI upon first use. Kuriakose et al. (2020) suggest that adding customizability to a user interface in the form of user preferences in settings allows the user to mold the experience to suit their specific needs. Janidarmian et al. (2018) testing for recognition in a haptic feedback language similar to the one described by Novich & Eagleman (2015) relate that providing test participants with the option to customize feedback signals resulted in higher learning acquisition rates. Thus, the literature suggests that incorporating easy, accessible learning as well as customizability options within the NAVI user interface can serve to enhance usability and user experience goals. These accessible learning and customizability options are particularly relevant when introducing complex feedback methods.

2.6 Familiarity & Intuitive Design Approach

Traditionally the blind and visually impaired have relied upon the white cane and guide dogs to aid in mobility and obstacle avoidance. Tyagi et al. (2021) note that though technological alternatives abound, these have failed to supplant traditional aids. Accordingly, proposals for NAVIs in the literature are frequently positioned as complimentary to traditional aids. In Ahlmark (2022) the Laser Navigator is designed to augment the range afforded by the white cane, providing customizable range settings that extend up to 50 meters. In the market, examples of NAVIs as augmentations to traditional methods abound. These include solutions such as SmartCane, GuideCane and Ultracane all of which make use of the familiar format of the white cane. According to Payyanur (2019) leveraging an existing format, one that is familiar and approachable to the user can improve user retention by reducing the required learning curve. This reduced learning curve facilitated by familiarity with a product is particularly relevant in smartphone based NAVIs where existing user interfaces and widespread use allow for greater distribution. Greater distribution in turn directly impacts price. Messaoudi et al. (2022) note that the cost of a NAVI will determine its accessibility for the user. Tyagi et al. (2021) also suggest that the compatibility of a NAVI with preexisting technologies will influence its implementation in daily use. In this regard, smartphones provide the highest value in terms of integrated and compatible technologies for both users and designers. In addition to leveraging ubiquitous technologies in NAVI design to address cost and compatibility concerns.

Lloyd-Esenkaya et al. (2020) suggest that the benefits afforded by NAVIs to a niche user group can be extended to the wider population, providing more flexible interactions through multimodal means.

2.7 Challenges in Portraying the Physical Environment

In a review of smartphone-based wayfinding tools in urban settings, Swobodzinski & Parker (2019) conducted focus groups with blind and visually impaired users in an attempt to identify gaps in the current user experience. One such gap involves the lack of seamless real-time navigation between indoor and outdoor settings. This is in part a technological limitation. Marzec & Kos (2019) explain that indoor navigation providing real-time descriptions of places of interest requires BLE Beacons or RFID tags, the installation and maintenance of which can be a costly affair. The NavCog3 as described by Sato et al. (2019) details such a system. Providing indoor turn by turn navigation via speech, the NavCog3 is contingent upon the willingness of malls and public spaces to invest in additional infrastructure requirements. BlindSquare in contrast and as described by Nevin (2022) is one example of a wayfinding application offering indoor and outdoor functionality. However, this indoor funcionality is also contingent upon a given location's prior installation of beacons. Aside from infrastructure hurdles, findings of Swobodzinski & Parker (2019) suggest that wayfinding applications tend to narrowly focus on one or two tasks, neglecting the multifaceted nature of a user's complete trip including transitions related to public transport and intersections. Marzec et al (2019) adds that most current urban wayfinding solutions do not inform users about obstacles like curbs or poles and do not provide adequate descriptions of objects for localization. BlindSquare has sought to fill some of these gaps in usability by integrating public transportation data and augmenting its deployment of open-source platforms like FourSquare and OpenStreetMap with its own data for obstacle detection (Nevin, 2022). By their early and continued contact with the user group, the gap between daily user travel experience and the most useful information to be conveyed has been narrowed.

2.8 Emerging Technologies Shaping Feedback Methods

The strategy employed by the wayfinding NAVIs described above involves bringing places of interest including obstacles to the awareness of the user as they navigate through an environment. This occurs without the user having to actively scan their surroundings. Outdoors, this is most commonly achieved by synchronizing a user's GPS location with open-source map data. Audio or haptic cues in conjunction with descriptive speech help populate the user's situational awareness in real time. Aiordăchioae et al. (2020) notes that providing situational awareness of this kind to the user can now also be accomplished through the use of cameras embedded in wearable devices. According to Kuriakose et al. (2020) vision-based navigation makes use of computer vision algorithms, optical sensors and cameras in tracking the details in the user's environment. Ojala (2018) notes that the real time signal processing methods used by older NAVIs such as vOICe, EyeMusic and The Vibe have given way to new and more effective solutions made possible by computer vision and deep learning. Lo Valvo et al. (2021) describe such a NAVI based on computer vision algorithms which uses neural networks in conjunction with a virtual library to provide users with detailed information about places of interest. Kuriakose et al. (2020) notes that deep learning methods like neural networks are increasingly more efficient in detecting objects and thus ideally suited for supporting real time navigation in dynamic environments. Lock et al. (2023) propose the use of a progressive co-adaptive user interface wherein human centered and goal oriented deep learning algorithms are used to maximize usability and user experience. In similar fashion to customizability settings mentioned previously allowing the user to mold the interface to their specific needs, the progressive co-adaptive approach allows for this and much more.

2.9 Miniaturization Enhances User Experience

Wearable technologies provide portable, discreet and hands-free sensing and feedback delivery to NAVI users. Real & Araujo (2019) note that an overall decrease in the size and cost of microprocessors and sensors has led to an increase in wearable solutions for visually impaired users. According to Kuriakose et al. (2020) portability of a technology will strongly influence user acceptance. In addition to functional concerns, dos Santos et al. (2020) recommends that aesthetics be considered when designing for the visually impaired to avoid the impact of a "negative symbolic load" or the attribution of traits based on outward features and accessories linked to a specific identity. Kuriakose et al. (2020) stresses the need for NAVI designs to allow users more discreet navigation in public settings.

2.10 Wearables

Beyond the trend towards miniaturization enhancing portability and considerations for discreet and aesthetically pleasing wearable technologies, functionality is also closely linked with the choice of placement on the user's body that is best suited for transmitting a feedback language. Real & Araujo (2019) mention that NAVIs have made use of smart glasses with built-in cameras and bone conduction headphones that don't occlude sounds from the user's surroundings. In this example, placement neatly corresponds to the sensory organs for audition and sight, but for touch, the choices provided for by the skin require more careful consideration. Velázquez (2010) relates that placement for haptic feedback is directly affected by the capability of mechanoreceptors to process incoming sensory data. More precisely, this can be referred to as the two-point threshold. The American Psychological Association defines this as “the smallest distance between two points of stimulation on the skin at which the two stimuli are perceived as two stimuli rather than as a single stimulus.” The fingers feature a high density of mechanoreceptor distribution enjoying a two-point discrimination ranging from 2 to 8 mm. In the market, the prevalence of smart gloves and wearables for the wrist and fingers reveals design choices that reflect this consideration to seek optimal placement for a given feedback method. Additionally, Velazquez et al. (2018) relates that using haptic feedback requires less cognitive activity and is also ideal for conveying directional data. Velazquez et al. (2018) implement a haptic wearable shoe insert which makes use of directional information to guide the user to move forward, left, right or to stop. The Navbelt as described by Shoval et al. (2003) represents another example of a wearable deploying directional haptic feedback through the placement of actuators along the full circumference of the user’s waste. A more elegant approach to directional haptic feedback is described by Nevin (2022) using a single actuator in a wristband wearable. In this example, deviation from a predetermined route is signalled by gradually increasing haptic feedback provided in direct proportion to the user veering off course. A similar method of corrective haptic feedback is used by Moesgen et al. (2022) which in combination with other feedback modalities offers a non-intrusive means of communicating when a relevant threshold has been crossed.

2.11 Summary

This review has explored and examined literature detailing considerations essential to NAVI design. Based on the activity of capturing requirements as described in Sharp et al. (2019) these essential considerations have been aligned with the following categories: functional requirements, data requirements, environmental requirements, usability goals and user experience goals. Aligning essential considerations to requirements and goals in the early discovery phase of the design process has helped to reveal additional insights which contribute to more effective future NAVI design. Additionally, as NAVIs are communicative devices by their very nature, this review has prioritized data requirements, specifically feedback methods, according these a central position among other requirements and goals. In the following, a summation of key discoveries emerging from this literature review are discussed.

The Internal Environmental Requirements or neurocognitive features inherent to all humans serve as the foundation for understanding and implementing effective feedback methods. The following concepts are discussed in the literature.

- Neuroplasticity Theory describes the ability of the human brain to adapt and rewire itself in the face of novel external stimuli.

- Cross modal Correspondences reveal unexpected pre-existing links between cortical regions corresponding to different sensory inputs.

- The Meta modal organization of the brain suggests that more complex tasks facilitate greater cross modal sharing and integration of sensory data.

- Spatiotemporal Congruence is at the heart of this sharing and combination of sensory data as the perception of realness relies upon the coincidence in space and time of various sensory stimuli.

Sensory Substitution as a method of replacing one mode of sensory information with another, makes use of pre-existing links between cortical regions and relies upon the neuroplasticity of the brain in reinforcing and repurposing previously underused connections and areas in the brain. Through extended training, earlier Sensory Substitution methods in NAVIs aimed to achieve Synthetic Synesthesia, or the generation of cognitive forms akin to actual vision by using haptic or audio feedback methods. A review of the literature reveals the benefits as well as the drawbacks of extensive training, the latter affecting lower adoption of sensory substitution devices by users.

- Training in sensory substitution needs time to forge linkages between cortical regions that in turn help in generating vision approximating cognitive forms.

- Externalization or attributing realness in interacting with external objects through artificial feedback methods also needs time to develop.

- The prospect of extensive training periods in a new device is a deterrent to many users.

- The attention needed by the user in operating with a sensory substitution device in outdoor environments may occlude necessary awareness of natural external stimuli, thereby lending to the user experience a sense of feeling unsafe.

Traditional Sensory Substitution methods in NAVIs have not always been able to convey data about the physical environment in a way that is useful to the user. This is particularly true when feedback methods contain a high volume of data and are low in speed. In dynamic and busy surroundings, this can overwhelm the user. Therefore, different strategies in designing feedback methods need to be investigated based on the user's actual experience in the intended environments of use.

- Sensory constraints shape feedback methods.
- Sensory Bandwidth or the capacity of a sensory channel in processing data is lower in audition and touch as opposed to vision.
- Sensory Overload can occur when data received by a given a sensory channel exceeds its Sensory Bandwidth.
- Complex sensory substitution methods conveying a large volume of data are not ideal in busy and dynamic settings as they overwhelm the user and potentially occlude stimuli from the natural environment.

Regarding sensory constraints the literature suggests that designers of feedback methods consider the following:

- Sight allows assessment of the location and relative distance of objects in the environment at a glance. For the visually impaired, representations of the physical environment should be built in steps by providing data about landmarks and places of interest. This allows VI users to cognitively map their surroundings spatially and establish relative location in real time.
- Timing of feedback is also crucial for keeping the user in the loop and constructing a real time representation of the user's dynamic environment. This is particularly relevant for obstacle avoidance and navigating busy intersections.
- When constructing feedback, using a task-oriented approach as defined by the user's functional goals and the intended environment of use cuts down on unnecessary information.

Multimodal Feedback methods include a combination of audio, haptic or descriptive speech. In the literature, this method is recommended for the following reasons:

- Human cognition is limited in its capacity to receive, hold and process sensory stimuli. Spatiotemporal Congruity or the sense of perceptual realness is fortified by multimodal sensory stimuli.

- Transmitting feedback through a single channel, especially given the lower resolution of audition or touch, risks overloading that channel. A Multimodal distribution can help prevent sensory overload.

- A multimodal distribution of feedback limits occlusion of auditory stimuli from the natural environment. Haptic feedback is ideal for supplementing audio feedback.

- Multimodal feedback provides the user with flexible options in varied environments.

Providing users with the means to easily adapt to an interface upon first use allows users to more readily incorporate that interface within their daily routine thereby increasing usability. The following strategies for enhancing usability have been discussed in the reviewed literature.

- Incorporating training regimens into the user interface.

- Allowing for customizable feedback options. This has been shown to support higher rates of user acquisition of a feedback method.

Leveraging the widespread use of and familiarity with device format supports accessibility and usability and facilitates higher adoption rates. The benefits of integrating a widely used and standardized technology in deploying a new NAVI design as discussed in the literature are as follows.

- NAVIs are in some cases modeled on pre-existing non technological aids for the BVI community such as white cane, allowing for the user to intuitively understand how to use the new technology upon first use.

- Widespread use of ubiquitous technologies such as smart phones and tablets are leveraged by designers in the design of NAVIs. These technologies, by virtue of their operation being familiar to the user, reduce required learning times upon first use.

- Greater distribution of ubiquitous technologies also equates to lower costs for the user.

- Compatibility of NAVIs accessories such as wearables or other devices with ubiquitous technologies contributes to a higher likelihood of user adoption and increases usability.

- The benefits provided through NAVIs to the niche user group, in this case the BVI community can be extended to the general population. Multimodal feedback options can thus contribute to greater flexibility for all users of ubiquitous technologies in applications beyond the context within which NAVIs are situated.

- Navigation and other widely used services can also be designed inclusively to extend usability to the BVI community. Widespread use contributes to more rapid and consistent improvements that benefit all.

There is room for improvement in NAVIs currently operating from smart phones and tablets. The unmet functional goals and technical hurdles as mentioned in the reviewed literature are as follows.

- Seamless navigation between indoor and outdoor environments is rare in current NAVIs.

- Indoor navigation relies upon the installation of beacons. The cost and ongoing maintenance of beacons hinders wider usage.

- GPS accuracy in outdoor applications can be improved.

- NAVIs are limited in the number of tasks they perform. This does not serve the user in journeys that require navigating through varied environments and switching modes of transit.

- Current NAVIs have limited obstacle avoidance features.

Designers of NAVIs benefit from keeping abreast of emerging technical developments as these inform and support improvements in design. In addition to the integrated suite of capabilities contained within ubiquitous technologies that facilitate navigation such as GPS and open-source maps, the following developments are discussed in their capacity to further improve NAVI design.

- Camera vision algorithms and deep learning methods allow for better real time access to the user's environment through landmark and POI descriptions as well as better depth perception and obstacle avoidance.

- Progressive Coadaptation methods support adaptability and the continued growth and learning of the user thus enhancing usability.

Exploring technical developments in the literature also reveals that user experience has benefitted from gradual miniaturization of technologies. The following have been discussed in the reviewed literature.

- Portability has been enhanced by the trend toward miniaturization. Greater portability leads to better usability as the user is unencumbered by weight or size in daily usage.

- The social stigma of wearing or carrying a heavy or bulky and aesthetically unappealing technology has also been an inhibiting factor when considering older NAVI devices.

- The level of discretion afforded to NAVI users has been enhanced by the trend toward miniaturization. Sensitive data expensive technology can be adequately concealed or worn in a way that supports the user in feeling safe. As NAVI accessories, the wearables market exemplifies the convergence of the considerations of portability, aesthetic value and discretion.

The choice of wearable placement for a NAVI accessory transmitting feedback is directly informed by the sensory channel to be used. With haptic feedback, choice of placement on the skin is related to the following factors.

- Distribution of mechanoreceptors in the skin varies considerably. The fingers enjoy a dense distribution of mechanoreceptors, yet gloves commonly used to transmit haptics in the VR context may make the user stand out in a public setting. Therefore, physiological as well as sociological concerns must match for optimal user experience.

- Directional feedback is ideally suited to haptic applications as belts and wristbands can provide a 360-degree correlation to the physical environment.

- Corrective feedback informing the user when a threshold is crossed or when deviation from the correct predetermined action is occurring, is an ideal nonintrusive feedback method that also helps conserve energy and avoid sensory overload.

- In providing directional guidance, corrective feedback has been shown in the literature to require the use of less actuators.

3 Research material and methods

The task of designing assistive navigational aids for the visually impaired requires that designers develop familiarity with a range of topics that together help build a more cohesive picture of the requirements that contribute to an effective design solution. According to Sharp et al. (2019) discovering requirements in the initial phase of the design process helps designers to further define users' needs, what tasks and goals need to be accomplished in supporting those needs and constraints that will affect performance outcomes. In using the requirements framework to build a more cohesive picture, data requirements, specifically feedback methods have been prioritized in this research as NAVIs are fundamentally communicative in function. Therefore, additional requirements discovered within the context of this research are viewed in relation to this communicative function. In the research that follows, we continue to focus on the discovery stage of the design process as it corresponds to the activity of capturing requirements proposed by Sharp et al. (2019). Through analysis of data obtained in interviews with experts, requirements for NAVI design identified in the literature is further expanded.

An exploration of NAVI design as it is presented in the literature provided the basis for a rudimentary understanding of the problem space. Through data collected in this exploration a more informed set of questions were drafted with the intention of further defining discovered requirements and exploring the reasons for low NAVI adoption rates among the target user group. These questions were then deployed in seven expert interviews (Table 3.1). As the aim of these interviews was to add additional depth to the topic and to discover aspects of the design journey not revealed in the literature, a semi-structured interview approach was adopted. According to George (2022) exploratory research can benefit from the flexibility afforded by semi-structured interviews as unexpected answers received may adjust the research trajectory. In the first set of interviews, participants were selected based on previous research projects in the field or experience with NAVI products in the market. Later as the interview process unfolded, additional connections were established with experts in sensory substitution and XR design in order to explore relevant cognitive features and technical developments relevant to the design of NAVIs in greater depth (Table 3.2). Interviews were subsequently analyzed using thematic analysis methodology whereby coding was applied to transcribed content. Codes were then organized into themes based on the requirements framework presented in Sharp et al. (2019) and the relationships of these themes to the communicative function fundamental to NAVIs were identified.

Topic	**Question**

Defining Parameters	What are the main parameters of sensory substitution design and how would you prioritize or balance these? Where does one begin when thinking of developing SSD?
Unimodal vs Multimodal Feedback	What are your thoughts on unimodal vs multimodal means of conveying information? When might you use one over the other?
Vibrotactile vs Audio	Are there advantages to using one form of feedback over another?
Intuitive First Use vs Training	How can an assistive technology that's easy for the user to grasp upon first use be compared with one requiring a training period? When is one or the other a good idea?
Neurosciences	How have understandings emerging from the cognitive sciences informed the way you develop feedback systems?
Sensory Overload	When considering communicating a representation of the environment to the user, how much information is too much?
Low Adoption Rates by the Blind and Visually Impaired	What might be the reason behind the low adoption rates of assistive technologies among the Blind and Visually impaired. Has the situation changed? How? What are some ways that adoption rates might be increased?
Academia vs Marketplace	How do academia and the marketplace differ in their handling of NAVI projects?
Ubiquitous Technologies	What is the role of ubiquitous technology in relation to the current NAVI market?
HCI and Fine-Tuning in the Test Phase	How has HCI played a role in the way that you develop your projects?
Heterogeneity of Target User Group	How does the heterogeneity of the Blind and Visually Impaired community complicate or inform your process when testing a prototype for instance?
Navigation and Obstacle Avoidance.	In terms of vibrotactile or haptic feedback, what would you consider to be

	the best way to provide a visually impaired person with information about navigation and obstacle avoidance? Is there at this point a standard or guidelines which a developer or designer could follow?
The Role of Landmarks in conveying a more comprehensive picture of the environment	How do landmarks figure into NAVI design? How would this type of information be best communicated?
Recent Innovations	What are some scientific/technological advances or even game changers that have emerged in recent years?
Directional Force Feedback, Repulsion/Attraction, Saltatory	Which types of vibrotactile feedback do you consider to be most useful in NAVI design?

Table 3.1 Interview Questions

Participant	**Recruitment Relevance to Topic**	**Duration/Time**	**Date**
P1	Research Engineer in several NAVI projects developing a laser range finder extending white cane range with haptic feedback.	13:00-14:15	18.01.23
P2	Developer and co-founder of company providing haptic navigational wearable for the visually impaired.	19:00-20:00	06.02.23
P3	XR Interaction Designer working with haptic prototyping in VR settings.	20:15-21:15	06.02.23
P4	Researcher at Aalto working with haptic gloves in various applications including biomedical & industrial/work applications.	14:00-15:00	08.02.23
P5	Developer and founder of in-the-market NAVI app using ubiquitous integrated capabilities of smart phone, GPS, OSM & FourSquare.	19:00-20:00	01.03.23

P6	Designer of in-the-market toolkit for prototyping haptic interactions.	11:00-11:45	09.03.23
P7	Biomedical Ebgineering and Computational Science. Graduate student formerly at Aalto working with a visual to audio sensory substitution deep learning project.	20:00-21:00	28.03.23

Table 3.2 Recruitment of Interview Participants & Relevance to Research Topic

After a review of literature detailing NAVI design projects as well as an exploration of NAVI products in the market, potential participants once identified were contacted by email and invited to participate in online interviews via Zoom or GoogleMeet. Aligning with the ethical research conduct guidelines described by Bolderston (2012) potential participants were provided with the following information and guarantees in advance of conducted interviews. The initial email invitation consisted of a synopsis of the research to be conducted. This included mention of the duration of interviews, primary research questions, an invitation for further clarification of the research topic, guarantees of anonymity and the option to withdraw from the research at any time (Appendix 1). Once having agreed to participate, participants were sent a privacy notice and a consent form to be signed and returned before the date of the interview (Appendix 2). In addition to emails sent through institutional channels, calendar invites were helpful in time management. To this end Calendly and Google calendars were used. Duration of interviews was set flexibly at 45 to 60 minutes and in most cases the full time was utilized. At the beginning of each interview, the participants were verbally guaranteed anonymity and the option to withdraw from the research at any time. The research topic was then briefly introduced and the recording initiated.

In selecting interview participants, expertise in NAVI design was prioritized. The doctoral thesis of participant 1 is based on several years of research into developing devices for obstacle detection that extend the limited reach of the white cane. In this research, the feedback method employed is simple and intuitive. To provide contrast in terms of feedback complexity, participant 7 explores more complex visual to audio sensory substitution methods. Participants 2 and 5 in turn, have developed commercially available NAVIs. In these cases, the circumstances differ somewhat from those encountered within the context of academic research as mentioned with participants 1 and 7 as there is an ongoing need for developers of commercially available NAVIs to engage with and be accountable to the target user group. In addition to experts having direct experience with NAVI development, this research recruited participants with XR backgrounds as the feedback methods and design tools and principles used in AR and VR applications can easily be applied to NAVI design. XR designers aim to accentuate the perception of realness in the experiences they design. In doing so the feedback methods they deploy conform to the same constraints of sensory perception that apply to NAVI design. The masters' theses of participants 3 and 6 involve the creation of digital tools that allow designers to craft custom feedback systems for any application. The emergence of such digital tools has major implications for how designers can test and prototype their designs going forward. Finally, participant 4 provides a diverse experience having designed assistive tools for the deaf, visually impaired, and more recently, stroke victims. Through the interview with participant 4, valuable insights were obtained on the topics of cross-disciplinary collaboration, testing of feedback methods and engaging with the target user group.

Interview questions were drafted to both confirm considerations already discovered from the literature and to expand beyond these into unknown territory. For efficient management of diverse topic matter, topics were aggregated in a chart from which open-ended questions could be generated (Table 3.3). After the first interview, this chart of aggregated topics was used in place of formalized questions as these could be quickly adapted to each interview and the individual experience of the participant. Looking into each participant's background, including research papers and work experience allowed for the interview process to yield deeper and more rewarding insights.

Interview Topics
Defining Parameters
Unimodal vs Multimodal Feedback
Sensory Overload
Sensory Bandwidth
Directional Force Feedback, Repulsion/Attraction, Saltatory…
Vibrotactile vs Audio
Intuitive First Use vs Training
Cognitive Science
Navigation and Obstacle Avoidance/Layering of Feedback System
Ubiquitous Technologies
HCI and Fine-Tuning in the Test Phase
Heterogeneity of Target User Group
Haptic Library/Open Source/Ecosystem for sharing haptic designs
Recent Innovations

Table 3.3 Interview Topics

According to Vaismoradi et al. (2013) a deductive research approach tests an established theory by applying it to new circumstances. In this research, specific requirement categories as described by Sharp et al. (2019) are applied through a thematic analysis of data obtained in expert interviews. Sharp et al. (2019) claim that discovering and capturing requirements earlier in the design process helps designers to implement more effective design solutions. However, NAVI design presents a complex landscape, one informed by a quickly changing social and technological environment. To keep pace with this dynamic environment, this research draws from the experiential knowledge of experts in arriving at unforeseen insights. Vaismoradi et al. (2013) describe qualitative approaches as ideally suited for understanding a phenomenon through the insights of those directly experiencing that phenomenon. In this case, these insights are arrived at through processing data obtained through interviews with experts currently, recently or peripherally involved with NAVI design. Of the qualitative approaches, Braun & Clarke (2006) state that thematic analysis is well suited for the identification of patterns within a given dataset. Therefore, thematic analysis methods are used here in discovering patterns stemming from interview data that both confirm existing insights from the reviewed literature and reveal new insights beyond the reviewed literature.

After conducting each interview, recordings of these were processed in several stages culminating in a code book consisting of quotes corresponding to codes organized into themes based on the proposed requirements framework in Sharp et al. (2019). A chart of codes organized into themes can be seen in Table 3.6. At the conclusion of each interview, recordings were transcribed using the Transcribe IOS application. Textual separation of interviewer from interviewee was performed manually through listening and editing and all terms and names by which a participant could be identified were anonymized. To further clean up the transcripts, redundant or unclear words were omitted or edited. Upon completion of the editing process, the interview recordings were deleted and edited transcripts were placed into charts where codes and explanations for codes could be applied (Appendix 4). The quotes for a single interview were then collected under a code heading to be viewed as a whole. To view the data set in totality, the collected codes and quotes from all interviews were fed into Delve online content analysis tool where the quotes belonging to a single code could now be compared. Finally, themes were applied to codes reflecting the requirements framework. These themes include usability goals, user experience goals, functional requirements, data requirements, physical environmental requirements, technical environmental requirements and internal environmental requirements. Two additional themes outside the requirements framework were added to the analysis in order to capture trends and design tools described by participants within the context of expert interviews. Developments & Trends describe larger cultural or technical developments and phenomenon that also impact NAVI design. Design tools in turn describe a set of methods and mindsets designers can use throughout the iterative design process. Design tools also help designers to leverage larger cultural and technical phenomenon to add efficacy to their design solutions.

Theme	**Code**
Internal Environmental Requirements (Neurocognitive Features)	Bandwidth Limitations
	Sensory Overload
	Sensory Substitution
	Sensory Perception
	Immersion/Multi-sensory Integration
	Skin Receptors
	Tactile Phenomenon
Usability Goals	Accessibility of Interface
	User Preferences/Customizability
	Need for Training
User Experience Goals	Low Adoption Rate
Funcional Requirements	Contact with User Group
	Use Case Specific
Design Approaches	Inclusive Design/Scale
	Intuitive Design
	Testing/Exploration
	Cross-Disciplinary Collaboration
	Prototyping
Data Requirements	Multimodal Feedback
	Feedback Type
	Feedback Language
Physical Environmental Requirements	Source/Input
Technical Environmental Requirements	Necessary Components
	Wearables
	Smartphones/Tablets
	Bone Conduction Headphones
	Tags
Developments & Trends	Advances in Technology
	Ubiquitous Technology
	Miniaturization
	Integration of Haptics (as a cultural phenomenon)
	Standardization

	Democratization
	Haptician/Haptics

Table 3.6 Themes & Codes

4 Findings

This section describes findings gathered from seven expert interviews on the topic of NAVI design. Interview content, further processed through thematic analysis, helped to reveal requirements essential to designing NAVIs and patterns in the approach taken by designers when considering requirements necessary to such design. Additionally, the data exposes larger technical trends and phenomenon that can be leveraged by designers in developing more accessible NAVI solutions.

4.1 Requirements & Goals

4.1.1 User Experience Goals

In the interview process, discussion about user experience was elicited by mention of low adoption rates of NAVIs by the visually impaired community. According to Sharp et al. (2019) user experience pertains to the externalities or perceptions about a product upon first use, its cost, how it feels and how it looks both to the user and to observers. Participant 1, both a developer of NAVIs and a member of the visually impaired user group, provided insights into concerns expressed to him by this group as these relate to their user experience with his and previous NAVI prototypes. These concerns included cost, size both from a portability as well as from an aesthetic standpoint and the perception of safety and trust experienced when using a NAVI device. As a result of consistent inadequate user experience, users may grow disillusioned when presented with new devices. Participant 1 reports on VI users often feeling that "this (device) wasn't really designed with the target user in mind." For instance, the "bulkiness" of a device can contribute to social stigmas. In this regard, participant 1 relates, VI users "don't want to stick out so much in their surroundings" and "might not want to look like a cyborg!" In discussing the price of his in the market NAVI wearable, participant 2 states, "it was just a heavy cost to put on people who are already economically disadvantaged." Finally, in considering user trust when navigating "an environment that can be threatening" participant 1 states, "it's important to feel comfortable with the device."

In Table 4.1, mention of user experience goals in the literature can be seen to neatly correspond with interview data. The degree to which these goals including low cost, portability, aesthetic value and discretion are positively expressed in a NAVI will impact adoption and continued use by users. According to Lloyd-Esenkaya et al. (2020) up to 30% of NAVIs are abandoned before they are adapted to everyday use. This can be attributed at least in part to poor user experience. As a means to adequately address user experience goals, interview participants describe direct and continued contact and consultation with the user group. Contact with the user group is further discussed in the section on Functional Requirements. External trends outside of designers' control such as the miniaturization of components over time as mentioned by Real & Araujo (2019) have also positively affected user experience with NAVIs. This topic is more comprehensively discussed in the section on Miniaturization, Advances in Technology & Wearables.

Literature		**Interviews**	
Lloyd-Esenkaya et al. (2020)	Up to 30% of NAVIs abandoned before regular use		
Real & Araujo (2019)	Miniaturization contributing to portable, discreet solutions		
Kuriakose et al. (2020)	Portability contributes to user acceptance	Participant 1	Perception of comfort
Kuriakose et al. (2020)	Discretion in public is important for user acceptance	Participant 1	Perception of safety, trust
dos Santos et al. (2020)	Poor aesthetics contributes to social stigma	Participant 1	Appearance in public
Messaoudi et al. (2022)	Cost determines accessibility to user	Participant 2	Cost of NAVI reduced for accessibility

Table 4.1 User Experience Goals

4.1.2 Usability Goals

According to Sharp eat al. (2019) usability describes the ease with which a user can grasp a new interface and the features that support the user in everyday use. In the data analysis, usability goals were collected by coding for accessibility, customizability features and the need for training required by users when adopting a new NAVI solution. When discussing accessibility, participants often refer to the user's ability to grasp the workings of a device upon initial introduction. Thus, excessive complexity in an interface can be seen as potentially detrimental to facilitating accessibility. In a discussion about the customizability filters of an iPhone supported NAVI, participant 5 relates, “yes, so I do have filters of course, but I also want to make defaults as good as possible. “ Noting that ease of accessibility can foster trust, boost usability and serve as a gateway to added complexity participant 1 adds, “an entry level device here would make sense that people can use, can learn to use easily and can trust because when we do this and we feel that we can trust it, we will bring it along, we will use it and then we will start to see more possibilities down the line for more complex devices.” Participant 2 also describes extending limited customizability through app settings where a user “can set it to 90s and 20s, 45s, right but whatever you set it to, it registers that you turn that far off, you get a vibration, and the vibration is tiny.“ Acknowledging the challenge of designing an interface with accessibility in mind for the heterogeneous VI community, participant 1 states that, “if you try to design a device for everyone while people are so different then maybe no one really feels like this device is for them so it has to be a customizable thing and when we say that you should be able to customize this we also then have to intentionally make this a bit more complex.” Accessibility to a new NAVI interface might also be enhanced by the addition of a means for users to build proficiency. Participant 1 in conceptualizing a potential NAVi makes the suggestion that,”there could be a training program built into an app.” Participant 3 describes his own inability to grasp simple feedback patterns presented in Apple Map’s navigational guidance on the Apple Watch and relates this experience to potential VI users stating, “they would probably need a learning curve, like where a voice says this is left and then it plays and this is right and then it plays. And then maybe with a game or something, it's like learning vocabulary with Duo Lingo.”

In Table 4.2 a description of usability goals found in the literature reflect those obtained through expert interviews. The ability of the user to easily use a NAVI interface is prioritized over customizability options. However, customizability options and settings also allow the user to mold the interface to suit their individual needs in daily use. This is important to consider as the VI community exhibit a wide range of differences in visual conditions. Acknowledging individual differences and the heterogeneity of the VI community, the research of Janidarmian et al. (2018) suggests that extending customizability to users to modify feedback signals improves the user acquisition of a feedback language. In the interviews, participants 1 and 3 also suggested the need for training to be featured in the interface as a means to enhance user accessibility. Kuriakose et al. (2020) warns however that shorter training times lead to greater user acceptance. Thus, designers of NAVIs must weigh the benefits of ease of accessibility against customizability and training features when designing a user interface.

Literature		**Interviews**	

Kuriakose et al. (2020)	Reduction in training time leads to greater user acceptance	Participant 5	Provide customizability but make default settings as good as possible to facilitate accessibility
Messaoudi et al. (2022)	UI should help users learn to operate NAVI upon first use	Participant 1	Easy to learn interface builds trust, can serve as a gateway to more complex interactions
		Participant 3	Basic training/game built in to interface
		Participant 1	Basic training built in to interface
Kuriakose et al. (2020)	Adding customizability options allows user to mold experience to their needs	Participant 2	Extending limited customizability
		Participant 1	Added customizability means greater complexity but allows user to make it their own
Janidarmian et al. (2018)	Feedback customizability contributes to higher feedback acquisition rates		

Table 4.2 Usability Goals

4.1.3 Internal Environmental Requirements

In Sharp et al. (2019) physical, technical and even social environmental requirements have been discussed as these provide a framework for understanding the multiple contexts in which a design problem occurs. In this research, internal environmental requirements have been introduced as a theme for addressing the complex role played by human sensory perception when considering effective feedback patterns for NAVIs. As NAVIs aim to translate information received from the physical environment from one sensory modality to another, it is important for designers to understand how this information can be optimally received and processed. Here participants discuss neurocognitive features that both inform and constrain feedback languages.

The constraints on NAVI feedback methods are in part due to limitations in sensory bandwidth, or the amount of sensory data that can be processed by one sensory channel. These limitations are best exemplified by participant 7 stating, “there's no way for you to translate a general visual scene into a sound representation that would contain all the information that could be learned by a human.” Confirming this view, participant 1 states, “that when you try to substitute a sense, you’re only doing this part way so we can substitute a set of stimuli from one sense to another but that doesn’t get the whole world experience across.” Limitations imposed by sensory translations require designers to decide which information is possible and most relevant to present to a user through feedback. Participant 1 discusses this challenge in relation to the high bandwidth of visual information stating, “you get a lot of information very quickly and this is the tricky issue to convey with other senses so you have to filter and what parameters can you use to filter the information?” According to participant 2, the richness of the visual domain as well as the limits to speed of transmission to alternative sensory channels requires that designers, “look at the senses and optimize them for the parts that they're great for.” For instance, through the use of descriptive feedback, a mental cognitive image of an object is generated but conveyance of directional or locational information related to that object are more effectively communicated by haptic feedback methods. As a feedback method haptics are more immediate whereas sound, particularly in its descriptive form takes time to process. Participant 2 states, “sound is linear. To understand what I'm saying you have to wait as a time period to the end of my sentence to get the understanding of what I'm saying, right?” Noting the limited informational capacitity of haptics as compared with sound, participant 7 maintains, “if you compute the bandwidth of what you can have with haptics, it's not a lot.”

In addition to the challenges posed by bandwidth differences when translating information across sensory modalities, participants discussed deploying feedback with moderation, particularly when utilizing a single sensory channel so as to avoid sensory overload. Addressing the potential to overload the sense of touch, participant 6 relates, “it's the first sense that we are developing and we are very sensitive because it's about, you know, physical communication, touch, et cetera. So that's very deeply integrated into our perception, and therefore also like every time something is vibrating, it takes my focus and it can be very overwhelming if not done in a meaningful matter, so the amount needs to be tuned to the application. "Participant 4 echoes this concern stating, "if you have too much vibration going on, it can be also very confusing." Working with developing functionalities for haptic gloves, participant 3 describes his experience with sensory overload as follows, "they were overloading my fingertips and I didn't know what it tried to communicate because there was too much happening." In an attempt to limit sensory overload, participant 4 describes the use of haptic feedback in a corrective capacity stating, "the feedback was usually off and they only turned on when you made a mistake just to make it not annoying and not overwhelming."

Feedback must also be balanced with stimuli from the external environment which may be crucial for the user in maintaining situational awareness. This consideration is especially relevant when considering audio stimuli. Raising this concern, participant 1 states, "in a very complex environment you cannot just overload any sense in that kind of application." Participant 5 describes an in the field observation of a blind user utilizing a rudimentary form of echo-location with the tap of the white cane stating, "it is super important to understand that you can't block hearing from the blind person. It is super important to leave their ears open." With some reservations, participant 1 describes technological advances that can now be deployed to address the potential for overloading audition as follows, "these (bone conduction headphones) could now be utilized better than it was back then but yeah still you have to be careful with how you use, there are many ways to overload, you can either block the air or you can just have too much coming in so you can't process it." Aside from technological means for avoiding overload of the auditory channel, participant 1 argues for multimodal feedback methods when claiming, "to spread out the load to other senses would be beneficial. "However, participant 3 expresses the dual nature of multimodal feedback solutions when stating, "audio (in addition to haptics) can help to create more vocabulary or to make use or to use more vocabulary, but yeah, it could also increase cognitive load."

Among the participants, 3 had prior and/or ongoing experience in developing functionalities within the context of extended reality applications. Through data obtained in interviews with these participants, an emphasis on designing for immersive experiences was revealed. The concept of immersive experience draws from the way in which humans process and combine information received simultaneously through multiple sensory channels. The multi sensory integration that occurs as a result of combining this incoming information creates the sense of realness that characterizes interactions of everyday life. Participant 3 describes multi sensory integration in these terms, "I think it's because of our experience with reality that when we, when objects collide, it creates a sound and when objects, and when my finger collides with an object, it creates a feeling of touch. So, when I do this, it creates a sound and it creates a feeling of touch. It gives me, my brain, the control system of my brain, it gets all these senses that this is real, this is an object, I can't go through it." In considering how this realness can be applied to NAVIs in order to enhance externalization, or the integration of motor activity with incoming sensory information as described by Kristjánsson et al. (2016) participant 7 states, "that's what it goes down to in the end, is that whether you can have a really fast feedback of what you touch, and what you hear. Cuz that's the only thing you can compare." Applying attributes that facilitate the sense of realness to NAVI feedback patterns involves layering sensory information for simultaneous experience. Exploring this sense of realness through layering, participant 3 relates, "I played in my thesis with the visual, at first with the visual cue. And on top of that I built the audio haptic cue and then, the audio cue and the haptic cue that matches to the audio cue. To make a feeling of pressing buttons as real as possible. Or giving the brain feedback that I press the button that I reached the specific threshold." In regard to refining simultaneous audio and haptic signals to augment the perception of a single event, participant 6 advises, "what you can do is actually take the auditory feedback as an advantage to further tune and shape the haptics, cause when they occur at the same time, I guess was it within five milliseconds or 10 milliseconds, uh, you will recognize it as a single signal." An expanded audio/haptic pattern repertoire can also be achieved by varying audio frequency superimposed upon the same haptic signal. Participant 3 relates, "double buzz with high tones and double buzz with low tones can be a difference. "

In Table 4,3 the constraints that human sensory perception place upon the design of feedback methods are described. Data obtained through interviews confirms understandings discovered in the literature. According to Kristjánsson et al. (2016) when communicating visual data through sound or touch, the limited bandwidths afforded by the modalities of audition and tactile sensation imply that a loss of informational richness occurs in translation. Adding to the limitations of communicating through sound and touch, conveying too much information can overload a sensory channel, especially if it obstructs the reception of sensory data from the user's physical surroundings. Thus, designers of NAVIs are tasked with determining which information is relevant or crucial in fulfilling the function that best serves the user. Kuriakose et al. (2020) state that only necessary information be conveyed to the user through a NAVI feedback method and that special attention should be paid to the timing of information conveyed. The importance of properly timed feedback is as Ahlmark (2022) states, due to the fact that sight provides environmental information at a glance, while sound and touch are limited and tend to supplement the overarching role of vision. Therefore, a visually impaired or blind individual maps their physical environment in steps, establishing their location through continuous updates in relative position. A feedback method that reflects this difference in achieving situational awareness must be considered when designing NAVIs.

Participants working with extended realities and VR or AR applications were keenly aware of the constraints that sensory perception imposed upon feedback choices within and beyond the NAVI context. The rapid developments in feedback methods and technologies occurring in the AR and VR contexts can benefit NAVI design particularly as these aim to accentuate the sense of realness in interaction with the user's environment. Kristjánsson et al. (2016) encourage extensive training with NAVIs in order to enhance externalisation or the sense of realness achieved through ongoing motor interaction with the physical environment through a given feedback method. Participants working with extended realities revealed methods that aim to accelerate and enhance the attainment of this sense of 'realness' by overlaying and fine-tuning feedback from multiple sensory sources, making use of the way in which human perception processes simultaneous sensory stimuli when constructing a wholistic picture of reality. Participants working in XR design also revealed that feedback vocabulary could be extended through the overlaying approach described. Multimodal feedback approaches mentioned in the literature have been used to distribute information across multiple sensory channels to avoid overload and occlusion of sensory stimuli from the user's physical surroundings. However, the simultaneity and additional fine-tuning of feedback described by XR designers opens new possibilities for NAVI design.

Literature		**Interviews**	
Kristjánsson et al. (2016)	Bandwidth of sound and touch compared with sight constrains feedback through the former two channels	Participant 7	Information inevitably lost when translating visual to audio
Ahlmark (2022)	Sighted individual gets environmental information at a glance, VI maps in steps	Participant 1	Cross modal sensory translations are only part way
Kuriakose et al. (2020)	Only necessary information, attention to timing	Participant 1	In light of bandwidth limitations, what information

			is important to convey?
Kristjánsson et al. (2016)	Perception is 'a continuous process not a snapshot'	Participant 2	Optimize feedback for what the particular sense is best at conveying
		Participant 2	Sound as linear and need to wait in order to process
		Participant 7	Haptics limited as compared with sound
		Participant 6	With touch, the amount of feedback needs to be in line with application, too much can easily overwhelm
		Participant 4	Too much vibration can be confusing
		Participant 4	Corrective haptic feedback used sparingly
		Participant 1	In complex environment don't overload senses
		Participant 5	Don't occlude audition
		Participant 1	Spread out load across senses
		Participant	Audio can help increase vocabulary but also can lead to overload
		Participant 3	Coincidence of stimuli creates sense of the real
		Participant 7	Coincidence of sensory stimuli with motor

			activity creates sense of the real
		Participant 6	Using coincidental audio to shape haptics
		Participant 3	Using coincidental audio to shape haptics

Table 4.3 Internal Environmental Requirements

4.1.4 Data Requirements

Sharp eat al. (2019) describe data requirements as including the value, persistence and amount of information that will be communicated with the user through an interface. When designing NAVI feedback for optimal communication with the mind of the user, it is first important to briefly consider the pathways that lead to the mind and the access points to those pathways. In terms of haptic feedback, this access point is our skin and the distribution of mechanoreceptors that sense touch and vibration, will dictate the placement of a specialized wearable interface. In determining proper placement of a haptic wearable, participant 3 states, “the resolution of your fingertip is very different to the resolution of your palm. So, here you have much more haptic receptors than maybe on your wrists or on your head. So, these are things that you also need to consider when you design for it.” Participant 4 confirms this in stating, “we are much more sensitive in the fingertips or fingers in general than, for example with the chest or back, so again, you have to think about, okay, what am I using the feedback for? and how can certain body regions support the feedback to fulfill, it's purpose or meaning.” A higher distribution of mechanoreceptors on the fingers allows for a higher resolution of information to be communicated into a smaller space. However, the directional properties afforded by a wristband or belt wearable may mean that optimal placement is not where resolution is highest. In this regard, participant 1 states that, “if we deal with haptics, there’s a natural correlation there with the visual space.” The NAVI designed by participant 5 primarily uses audio cues and descriptive speech to facilitate navigation. In discussing how directional information can be conveyed haptically with a belt wearable participant 5 states, “when I'm mentioning some place, I usually say clock faces. So, if it's, right of you, it's three o'clock straight ahead, 12 o'clock. But if you have that belt, it just mentions, uh, post office and it vibrates from here.” Correctional haptic feedback can also be used to guide along a predetermined trajectory. Participant 2 describes this type of guidance stating, “what we've done is that when you're in Pacman's mouth, you know, left or right of the center line, you feel nothing. So, you wave in this small area, you get no vibrations at all. If you then hit the edge of Pacman's mouth on either side, you get a tiny vibration. And then the more that you turn, like if, you know, once you are facing Pacman's butt, you can hit the loudest vibration." Conveying directional information is also possible through audio feedback. Participant 5, describing the use of stereophonic sound with a LiDaR application for directional feedback states, "and it was so fast that if obstacle was here, you would hear it from here. And if you turn, it is so fast that it pans this audio here. So, you really could avoid obstacles." Similarly, participant 7 also mentions the use of stereophonic sound stating, "there's 3D sound that you can generate, it not necessarily just have to come from the two sides. It could come from above or below, and like how accurately you can actually detect the difference."

In the discussion about the internal environmental requirements, bandwidth limitations and the potential for sensory overload constrain how feedback can be deployed. Participants agree that feedback should be distributed across modalities and used meaningfully or sparingly according to use case. Participant 7 advises to, "actually think about constraining the visual space that you want to be able to encode into sound." A multimodal distribution of feedback in NAVIs aligns with the way humans actually integrate multi sensory information and therefore contributes to building a sense of realness when interacting with the physical environment. Contemplating an ideal multimodal feedback system, participant 1 proposes, "let's say we have a haptic system to get a feel for the environment in some way and then we could have auditory feedback, not in like to try to replicate a sense but maybe a voice that tells you things." Participant 5 replacing haptic feedback with sound cues states, "you'll hear obstacle sound that is, sound is like 'blonk'. If you hit, it's out, out sound, and then you hear, gate five meters." Participant 7 also describes multimodal feedback with a descriptive element stating, "If the sound is abstract in a way that mine was, and in a way that voices, although voice can be understood better in terms of like, if you can make, I guess you can even describe it to a blind person, like what the voice does internally, and then can, in the brain kind of cognitively." Based on discussion with participants, the multimodal combination of a descriptive element with cues for distance, direction or detection seem to provide a more wholistic means of constraining the rich visual bandwidth down to the essentials useful to NAVI users. On the methods for expansion of a limited haptic feedback vocabulary used simultaneously with audio, participant 3 states, "you want to define between high and low pitch audio cues to differentiate haptic patterns from each other because you can't use more than maybe three or two. "Common or standardized understandings of feedback patterns can also be used when designing for NAVIs. Deploying rising and falling sounds cues for communicating success or failure to achieve a navigational goal participant 5 states, “and then when, if you reach the destination, next sound is, minor uh, major chord upwards, and if you miss it, minor chord downwards. “Participant 4 confirms this common understanding when stating, “there is some common ground, for example, deriving from the auditory feedback, if something is increasing, it's positive. Like if something is, falling, it's negative and you can use the same language as the same grammar, also for haptic feedback.”

Participants supported the concept of a simple and easily grasped feedback language over a more complex sensory substitution method. Sensory substitution methods aim to replace information normally received through one sensory channel with information from another. The quantity of information to be conveyed is voluminous and is intended to comprehensively approximate information from another sensory channel. Thus, adapting to such feedback systems requires additional time and training for the user. Also, the speed at which a user can process detailed visual to audio information is less than optimal. Participant 7 in describing the limitations encountered in a visual to audio sensory substitution project relates that, “the main problem with these algorithms is that they're really slow.” Condensing the amount of time needed to process information can be bypassed by simply supplying descriptive feedback. Participant 1 favors this approach when stating, “if we extend the concept a bit further from necessarily substituting so I’m thinking for instance, when I’m moving beside someone else who then can see and can tell me, hey there’s a staircase that works, that is not necessarily substitution in the way that I’m referring to it, like I’m not getting a sense of the staircase from any other way, so it’s rather a cognitive thing that I now know that there’s a staircase.”

In Table 4.4 specific attributes and approaches used by participants in constructing NAVI feedback methods are shown. As mentioned in the section on internal environmental requirements, a multimodal distribution feedback helps to prevent sensory overload. According to Kuriakose et al. (2020) a multimodal feedback distribution also adds flexibility to a NAVI when used in varied environments. Kuriakose et al. (2020) state that haptic feedback as an alternative to audio feedback prevents occlusion of stimuli from the physical environment that might occur in the use of the latter. Participants describe the placement of haptic wearables in communicating directional information. In this application, direction can be communicated through a belt or wristband wearable with actuators distributed around its perimeter. Correctional feedback is also described as a means to provide unobtrusive guidance in navigation whereby feedback is given only and in proportional relationship to the degree to which an undesired threshold has been crossed. Stereophonic audio feedback as mentioned by participants 5 and 7 reflect the example described by Lock et al. (2023) using spatialized sound to communicate distance, height and angular orientation of obstacles to users.

Participants 1, 5 and 7 also promote descriptive feedback as an optimal means of quickly communicating complex information about obstacles or places of interest. Finally, traditional learning intensive sensory substitution methods are described by participant 7 as impractical in light of current more immediately accessible feedback alternatives within which, as participant 4 mentions, standardised understandings of feedback cues already in common use can be leveraged in reducing the user learning curve.

Literature		**Interviews**	
		Participant 3	High resolution of fingertips in haptics/wearables
		Participant 4	High resolution of fingertips as compared with back, placement should reflect purpose or meaning of feedback
		Participant 1	Haptic feedback has correlation to visual space
		Participant 5	Clock faces in descriptive audio, haptic belt actuator placement correlates similarly to directions in physical space
Patil et al. (2018)	Haptic feedback does not occlude hearing	Participant 2	Correctional haptic feedback
		Participant 5	Stereophonic sound
		Participant 7	Stereophonic sound
Kristjánsson et al. (2016)	Recommends multimodal feedback	Participant 1	Multimodal feedback haptic with descriptive
Velázquez (2010)	Multimodal feedback to avoid sensory overload		

Kuriakose et al. (2020)	Multimodal feedback helps to avoid sensory overload and adds flexibility in varied environments		
		Participant 5	Multimodal feedback audio with descriptive
		Participant 7	Multimodal feedback audio with descriptive
		Participant 3	Sound to differentiate haptics, expand vocabulary
		Participant 4	Use common understandings, falling, rising to ease understanding
		Participant 7	Sensory substitution methods can be slow for user to process
		Participant 1	Descriptive feedback quicker alternative to traditional sensory substitution

Table 4.4 Data Requirements

4.1.5 Physical & Technical Environmental Requirements

Sharp etc al. (2019) describe physical environmental requirements as the surroundings in which the interface is intended to operate. For NAVIs this is normally divided into indoor or outdoor settings as each requires its own distinct approach. Participants with NAVIs in the market designed for navigation, obstacle avoidance, and landmark detection and description in primarily outdoor environments. The ability to present accurate data about physical environments is dependent upon the present capabilities of the technical environment. Those mentioned by participants include capabilities integrated within smartphones such as open source map data, GPS, depth sensing cameras, AI recognition and LiDar. In presenting a detailed description of the user’s physical surroundings, participant 5 describes continually updating data featured in the NAVI stating, “about obstacles, I have been working with Open Street Map data, OSM data and I have been creating my own data sources for intersections, point of interests and obstacles. So, it's kind of a new thing because if you look Open Street Map, you see there are fences, bollard, gates, stairs, but they are not in any data source for this kind of application, but I have them.” Participant 5 further states, “accuracy is only GPS accuracy, but still to know that there are stairs, now I can warn about stairs, or I can warn about gate, bollard, et cetera.” Acknowledging the emerging depth sensing capabilities provided by newer cameras in tablets and smartphones as well as AI recognition of objects as deployed through these newer cameras, participant 1 states, “so having a camera that can describe the route, so that in conjunction with a sensory substitution haptic device might be something.” Participant 3 also mentions camera technologies in their capacity to more accurately recognize objects and precise distances when stating, “If you would have sensors, the camera sensor that understands perfectly the environment like Tesla or whatever, and it sees a pillar in front of you…”

Table 4.5 compares mentions of technical environmental requirements that are currently improving capabilities for NAVIs in communicating the user’s physical environment. Computer vision algorithms, deep learning methods, depth sensing and AI-based description have increased the scope, speed and accuracy of what can be represented. Moreover, the situational awareness supported by such technologies as mentioned by Aiordăchioae et al. (2020) provides VI users a passive situational awareness that cancels the need to actively scan for obstacles. Providing situational awareness through notifications about landmarks, obstacles and their relative distances in real time provides a better approximation of the assessment of the user’s surroundings at a glance afforded by the sense of sight.

Literature		**Interview**	
		Participant 5	Continually updating data for better representation of physical environment
		Participant 1	AI/camera-based description of route providing more immediate mapping of surroundings

Aiordăchioae et al. (2020)	Situational awareness supported by cameras embedded in wearables	Participant 3	Camera vision and depth sensing provide more in depth depiction of surroundings
Kuriakose et al. (2020)	Vision based navigation, computer vision algorithms, cameras, optical sensors		
Ojala (2018)	Computer vision and deep learning		
Lo Valvo et al. (2021)	computer vision algorithms which use neural networks		
Kuriakose et al. (2020)	deep learning methods like neural networks ideal for obstacle detection and real time navigation		
Lock et al. (2023)	Progressive co adaptive interface		

Table 4.5 Physical & Technical Environmental Requirements

4.1.6 Funcional Requirements

Previously usability and user experience goals were explored as expressed through the experience of expert interview participants. In practice these requirements would be gathered through contact with the user group whereby user needs and goals could be assessed. Defining the use case, or the specific setting in which the NAVI solution is intended to be deployed further determines functionality and performance goals. Sharp et al. (2019) describe functional requirements as what the product or service is intended to do in accordance with the users' needs. Thus, interview data relating to specific use cases and contact with the user group were gathered and placed under the theme, functional requirements as a means to understand how designers of NAVIs connect with the users they aim to design for. In collecting information about the user group for a NAVI project, participant 4 relates that, "we did some interviews also learning just in general about how they use live navigation aids." When thinking about the timing of contact and level of involvement extended to the user group in the design process, participant 4 relates that in retrospect, “it makes much more sense to involve the people (users) also and much earlier in the process and in the problem definition.” Participant 5 describes maintaining ongoing contact with users having, “maybe 70 beta testers from many, many countries so always when I do something it is then tested among those and I know them well, and I get honest feedback.”

Data gathered on how participants assess functionality through examining the specific use case revealed that a task focused approach helped streamline designs and align these to user needs. In approaching a new design problem participant 4 recommends to “first look at the use context and maybe the tasks that the user needs to fulfill, needs to do and then think about how haptic feedback can be helpful or beneficial to fulfill these tasks.” When approaching a specific use case participant 3 describes first trying “to empathize with the user’s needs or what they try to accomplish.” In addition to this approach, exploring the intended environmental setting can help designers discover what specific information is important to convey. Regarding this approach participant 3 relates, “basically maybe there's a crosswalk, there are stairs in front of me. I have this stick in front to know where the stairs are, so navigation left, right, top side because there are cars in front of me or there is something dangerous. So, I would collect basically these kinds of things.” In a case presented by participant 5, a user shared concerns over carrying an unconcealed iPhone in public stating that, “if blind person in Mexico takes iPhone out from the pocket, it gets stolen.” Participant 5 relates, “suddenly after six months or so, I realized what if I say to iOS that my application is a music player, then I can get control of play, stop, next, rewind et cetera.” In this way a music controller was able to be used in conjunction with the iPhone, keeping the phone concealed and enhancing user experience and usability.

In Table 4.6, the importance placed upon gathering information directly from users in identifying gaps in user experience and usability as seen in the literature, is reflected in the data obtained through expert interviews. Swobodzinski & Parker (2019) conducted focus groups with users in an attempt to understand how smartphone based NAVIs can be improved. Similarly, expert interview participants describe interviews with users, ongoing contact and feedback sessions and involving the user in the initial problem definition when assessing functional requirements for NAVIs. In addition, exploring the intended physical environment where the NAVI will be used and empathizing with the users’ needs are suggested in the absence of immediate access to user input. Finally, addressing specific use cases can lead to breakthroughs that enhance user experience and usability goals for all users. In the case related by participant 5, the need to conceal a smartphone in

Mexico City for theft prevention is not applicable in Helsinki and yet the added feature of an external controller enhances usability for all users.

Literature		**Interviews**	
Swobodzinski & Parker (2019)	Conducted focus group with VI users to identify gaps in user experience	Participant 4	Conduct interviews & learn how they use navigational aids
		Participant 4	Involve users early on in problem definition
		Participant 5	Ongoing contact with beta testers
		Participant 4	First look at use context and tasks to fulfill
		Participant 3	Empathize with user's needs and what they want to accomplish
		Participant 3	Explore intended environment in which NAVI is to be used
		Participant 5	Specific use case scenarios can lead to breakthroughs that enhance UX and usability

Table 4.6 Functional Requirements

4.2 Design Tools

4.2.1 Intuitive Approach & Scale

Applying an intuitive approach involves facilitating a more accessible interaction with a new interface by deploying a format already familiar to the user. Prior familiarization implies that a certain level of standardization or even ubiquitous use has been achieved. Thus, as stated by Payyanur (2019) extending a design from an existing standard reduces the time required for a user to adapt to a new interface. Describing a digital version of a widely used assistive aid for the blind, participant 1 relates, “the cane is a good analogy here because many visually impaired or blind people use that. Even if you are not, you could easily grasp the concept of the cane.” When designing feedback patterns, participant 3 consults Apple’s human interface guidelines stating, “it's also a best practice to use templates and not always invent new patterns because it creates also new, things to learn and If you use the system wide haptic patterns for buttons for whatever, and your users don't get confused.” However even with access to guidelines, it should be noted that the standardization that results from common understandings about optimal haptic and audio feedback patterns is far from fully established. Participant 5 worked to build a standardized set of audio feedback patterns within the context of his own smartphone-based NAVI for the practicalities of conducting joint training sessions with users. Thus, when asked for feedback customizability options by users, participant 5 declined on the grounds that, “if you hear something you need to understand it needs to be the same sound for everyone.” Participant 5 also expressed the need for developing common understandings and standardization of feedback patterns on a larger scale, postulating, “if there would be kind of a creative common, some project that then would kind of define where it (feedback pattern) can be used.”

In Table 4.7, familiarity with device format and the application of common understandings in feedback methods are described both in the literature and in data obtained through expert interviews as enhancing user accessibility in NAVIs. Tyagi et al. (2021) claims that compatibility of a NAVI with preexisting technologies will increase everyday use. These pre-existing technologies can include traditional aids for the blind as well as ubiquitous technologies such as smartphones and tablets. Preexisting haptic and audio signal suites featured on smartphones also help designers to reduce the learning curve for users when applying a new feedback method. However, achieving wider consensus on usage and meanings for haptic and audio signals will require more extensive future collaboration.

Literature		**Interviews**	
Tyagi et al. (2021)	NAVIs in the market have not replaced traditional aids		
Ahlmark (2022)	Bases own NAVI solution upon the capabilities afforded by the white cane, extending range.	Participant 1	The white cane as a familiar format

Tyagi et al. (2021)	Compatibility with preexisting technologies will increase everyday use		
Payyanur (2019)	Familiarity reduces learning curve in when adapting to a new interface	Participant 3	Apple's human interface guidelines when designing feedback provides familiarity to user, easier to learn
		Participant 5	Standardized audio feedback for better joint training
		Participant 5	Proposes creative commons for feedback methods

Table 4.7 Intuitive Approach & Scale

4.2.2 Inclusive Design

Inclusive design involves scaling solutions for wider applicability while simultaneously promoting accessibility for smaller disadvantaged user groups. As NAVIs are intended for a niche user group, they do not benefit from the funding and rapid development enjoyed by products reaching wider user groups. According to Lloyd-Esenkaya et al. (2020) by scaling NAVIs to wider markets, designers can use the inclusive design approach as a vehicle for greater accessibility and affordability. In deploying this type of strategy, subscriptions to the NAVI wearable developed by participant 2 was now able to be offered to the VI user group for free. As participant 2 relates, "we started getting interest from companies like Airbnb, Disney who were interested in ways of navigating into our experience and that actually gives us the chance to create impact for accessible navigation at a scale that's much greater than we could have done by just selling (NAVI) subscriptions." Participant 5 echoes this approach stating, "it makes sense to do something that is good for all and then make sure it is working nicely for the blind." In support of scaling up in the early stages of development, participant 5 describes including only features that would be applicable for international use. Participant 5 relates, "I was asked, please make an application that gives bus stop information in Finland. I said, no. I want to do something that works everywhere." He adds that later such local features were included but not before the product was scaled for wider use.

In Table 4.8, two participants with NAVIs in the market describe their reasoning for adopting an inclusive strategy in their approach to NAVI design. Scaling up allows features developed in the context of a NAVI to benefit a wider user group. The financial burden of developing exclusively for a niche user group can also be addressed by applying an inclusive design approach to navigational aids for the general populace that also takes the needs of VI users into consideration.

Literature		**Interviews**	
Lloyd-Esenkaya et al. (2020)	Benefits achieved in deploying feedback methods for the VI user group can be scaled for wider usage.	Participant 2	Scaling to wider user group allowed NAVI to be offered to the visually impaired for free
		Participant 5	More practical to make interface that benefits all and includes the VI community
		Participant 5	Designed NAVI uniformly for better scaling to international usage

Table 4.8 Inclusive Design

4.2.3 Testing, Exploration, Prototyping & Cross Disciplinary Collaboration

Testing, exploration, prototyping and cross disciplinary collaboration were all mentioned by participants as a means of fine-tuning for enhancing usability. A NAVI may seem intuitive and easy to grasp yet cannot fully be assessed as such until tested with the target user group it aims to serve. In testing a NAVI prototype based on the capabilities provided by the white cane, participant 1 describes unexpected difficulties encountered by first time users stating, “they could use the device and they could understand how it worked very quickly but still it was different enough from anything else that it wasn’t easy overall.” As previously mentioned, the VI user group is heterogeneous, exhibiting differences in needs based on the varied degree and nature of the visual impairment in question. The user group's capabilities upon first time use of a NAVI are also influenced by generational differences that coincide with exposure to and facility with ubiquitous technologies. In acknowledging this limitation while testing, participant 1 relates, "it's probably important to mention in this context that we had only older people in our user group, people that were over 50 I think, and this might change this acceptance of assistive aids for the younger generation who is already used to apps and devices and so on." In considering this generational gap, physical differences such as age-related neurological concerns and how these may influence the design of haptic interfaces becomes relevant. Participant 4 relates, "I think customizability or adaptability is quite important for haptics because we cannot assume everyone has the same sense of touch." Participant 4 describes testing attractive and repulsive haptic methods with a mixed age group including stroke victims in an attempt to discover, "how do they experience these patterns and is the repulsive versus attractive more...does this like generally work for them, which one works better for them?" Testing how a feedback system will be interpreted normally precedes testing on how a prototype fulfills usability requirements. Initial fine-tuning can also be achieved by the designer testing the feedback system on his or herself. Describing this process, participant 7 relates, "I did it on myself and also I made sure that before I started doing it I was, building my models. I was building these deeper in models that would do the translation from image to sound and back." In addition to skills in coding when prototyping NAVI feedback systems, participants revealed a need to be knowledgable in electronics. Describing the prototyping phase, participant 2 states, "we were using arduinos, we were using kind of whatever we could find off the shelf to prove the point." However, as the NAVI design process reaches into several areas of expertise, designers cannot be expected to be experts in all areas. Participants mention the occasional need for cross-disciplinary collaboration. Participant 2 describes this collaboration stating, "we brought in a hardware team and was like, hey, we need to design a custom experience, you know, and that does exactly what it is that we need to do." Participant 4 in working with test subjects with neurological disorders states, "We were in contact, or we collaborated with the occupational therapists and with the doctors, so we always consulted them in design questions." In designing a set of audio cues for his NAVI, participant 5 describes working with a sound professional relating, "yes...sound designer who is blind. Who is a musician. Yeah. So, has all the stuff needed and knows, how to make it really short, but still telling a story."

In Table 4.9 challenges related to testing and prototyping are displayed. A review by Parker et al. (2021) revealed that NAVI research rarely took into account the etiologies of individual test participants. This approach does not adequately reflect the diversity contained within the VI community and thus may fall short of meeting user needs. Also, in testing an already heterogenous user group such as the visually impaired it is important to consider generational differences in terms of familiarity and facility with widely used technologies. Familiarity with these technologies can influence how easily an interface is grasped upon first approach. Differences in age can also correlate to physical or neurological differences that will complicate the reception of feedback for some users. Thus, testing methods must factor in all of the above-mentioned concerns to achieve optimal outcomes. Aside from testing in the most comprehensive manner, designers cannot be expected to be experts in all things. Therefore, collaboration with experts from other fields is necessary when approaching something as multifaceted as NAVI design. Participants describe collaboration with medical professionals, sound designers and hardware technicians when reaching the limits of their own expertise. Lastly, while designers are well served by skills in coding and electronics when designing NAVIs, emergent trends in prototyping may allow designers to bypass the need for such skills. These trends will be discussed in the section, Democratization.

Literature		**Interviews**	
Parker et al. (2021)	Review of 35 peer reviewed research papers, one criterion for selection being tests with user group, were scant with details of individual users' conditions.		
		Participant 1	A seemingly intuitively designed interface still needs user testing
		Participant 4	Age and neurological condition affect how certain feedback will be received, especially haptic feedback. Testing is needed. Customizability/adaptability needed
		Participant 7	Testing feedback on self when

			designing. Making adjustments before user testing
		Participant 2	Familiarity with electronics needed when prototyping
		Participant 2	Collaboration with hardware team
		Participant 4	Collaboration with doctors and occupational therapists
		Participant 5	Collaboration with sound designer/musician

Table 4.9 Testing, Exploration, Prototyping & Cross Disciplinary Collaboration

4.3 Trends

4.3.1 Miniaturization, Advances in Technology & Wearables

While user experience concerns such as size, cost, portability and appearance in public are crucial for designers to consider when designing for NAVIs, trends collected from the data revealed that ongoing technical developments help designers to more adequately address these concerns. Trends such as the miniaturization of technical components help mitigate perceptions of social stigma associated with older more unwieldly versions of NAVIs. Participant 1, publishing his research in 2016 notes that “the technology has changed but if we would do the prototype again, it would be much smaller and lighter.” Participant 4 echoes this sentiment when stating that “the problem is, often with these devices, they're bulky and weigh a lot and as with any technology it gets smaller with time and with development of new microprocessors and new technologies.” The trend towards miniaturization coincides with the wearables market which currently provides a range of aesthetically pleasing and socially acceptable options that can be used in conjunction with NAVIs. Among these options, the wristband format was most commonly mentioned by participants. In proposing the placement of a wearable that is most familiar to users, participant 4 relates, “so I have to pick a location on this arm and the wrist is also a common spot, to have a smart-watch, for example." Describing the evolution of a wristband wearable, participant 2 relates, "first we have more motors wrapped around the wrist and then the one that was facing the right way would always be vibrating." In a later iteration of the same wearable wristband design, a reduction in size is seen to coincide with simplification of design which leads to a more affordable option. Participant 2 explains, "we can simplify the cost, the price, the failure rates, more pieces more failure. And so we took it down to two motors and then we were like, hey, what if we could do this in one motor?"

In Table 4.10 participants 1, 2 and 4 confirm the claim made by Real & Araujo (2019) that cost and size of microprocessors and sensors has led to more wearable options for NAVIs. Thus, a trend toward miniaturisation coinciding with technological development adds value to NAVIs as reduced size and weight support more aesthetically pleasing, portable and cost-efficient alternatives. In describing the development process of a wristband wearable, participant 2 also makes use of this trend. Initially an armband using multiple actuators, the wristband format becomes possible only after available components are small enough to support such a format. The design is eventually simplified to use only one actuator with corrective instead of constant haptic feedback. Thus, gradual miniaturisation of the prototype is further augmented by design choices that lead to more cost and energy efficient solutions. Participant 4 also chooses a wristband wearable format as it mirrors common usage and as such does not contribute to social stigma.

Literature		**Interviews**	
Real & Araujo (2019)	Cost and size of microprocessors and sensors has led to more wearable options for NAVIs	Participant 1	Prototype if designed today would be much smaller and lighter
		Participant 4	NAVIs are bulky but with time, technology improves and allows for lighter, smaller versions
		Participant 4	Wristband, commonly used placement for a wearable, doesn't make the user stand out in public

		Participant 2	Simplification of wearable reduces cost, increases efficiency, size and durability

Table 4.10 Miniaturization, Advances in Technology & Wearables

4.3.2 Ubiquitous Technologies

In addition to the trend towards miniaturization and the emerging wearables market, it is important to mention the underlying role played by ubiquitous technologies in enhancing usability. The integrated capabilities contained within ubiquitous technologies such as smartphones, tablets and now wearables provide designers with a pre-existing and quickly developing and deployable model to work from, one already familiar to users. On leveraging ubiquitous technologies with NAVIs participant 1 states "you might lower the barrier of entry to these devices by utilizing the attributes of the phone in various ways and because of people being used to their phones already you can use it regardless of how they do it." In a similar regard, participant 4 states, "we don't need to get people to buy extra devices, but we use these existing technologies that are also capable of playing feedback." Here another facet of the integrated capabilities afforded by ubiquitous technologies extends to standardized and readily deployable haptic feedback patterns which designers can also leverage when designing NAVI feedback systems. In this regard, paricipant 1 states, "take an off the shelf thing like I have, the Apple watch on my wrist, that has quite a sophisticated haptic engine in it so even that could be used through an app to communicate something."
Using open data and GPS as integrated features of smartphones in developing a NAVI, participant 5 relates, "and I didn't even know any blind person, but I figured out that there are so much open data available that if I can make an application that you can keep in your pocket and just walk and it'll start describing the environment that might be something."

In Table 4.11 interview participants confirm the claim made by Tyagi et al. (2021) that NAVI compatibility with preexisting technologies will increase everyday use. Leveraging familiarity with smartphones as well as the integrated capabilities contained within these allows designers to reduce the user's learning curve when adopting a new NAVI. Access to open data and maps that can augment depiction of the physical environment, as well as standardised haptic suites that can be repurposed for customized feedback systems also reduces costs for developers and users. For designer's, this lowered barrier of entry to NAVI development implies that more can be accomplished in a shorter time span. For users in turn, it is more likely that a NAVI app, readily available on their smartphone will be adopted.

Literature		Interviews	
Tyagi et al. (2021)	Compatibility with preexisting technologies will increase everyday use	Participant 1	Leverage the familiarity of smartphones in NAVI design
		Participant 4	Use existing devices with existing feedback. Familiarity and cost
		Participant 1	Apple watch preexisting haptic suit can be leveraged in NAVI designs
		Participant 5	Open data and gps used in NAVI application

Table 4.11 Ubiquitous Technologies

4.3.3 Democratization

The multifaceted nature of NAVI design requires that designers be familiar with electronics and coding when building prototypes. Moreover, they must become familiar with the intricacies of sound and haptic design used in these prototypes. When expertise is needed, cross disciplinary collaboration can assist in addressing challenges within what is normally a very involved and time intensive design process. However, this is not always possible and a lack of specialized skills and knowledge continue to constitute a barrier of entry for designers looking to build and test prototypes for NAVIs. This is particularly true when designing haptic feedback in wearables. Regarding this barrier, participant 6 states, “the threshold was just so high, where you would require expertise in electronics and software development, psychology, physiology to just get like a simple prototype going.” Exposed to these concerns from the design community, participant 6 sought to address this challenge by creating a platform rendering the design of haptic interfaces more accessible to designers. Describing the genesis of the platform, participant 6 states, “so this was the outcome of my thesis, basically a vision, a concept for a software part that's no code and where you can design the haptics as simple as like working with Adobe and creating an auditory track or cutting a movie." In reference to the platform designed by participant 6 and how it extends additional accessibility to prospective designers, participant 3 states, "you get a DEF kit where you can just take your actuator, attach it, and then also add a trigger, whatever trigger it is, you can code something with arduino or just use the system to explore how it feels." In describing the convenience afforded to designers by the platform, participant 4 states, "it already has the connections and different motors and you just need to play with it." Describing the creation of a similar platform, extending more modest haptic and sound design possibilities to designers, participant 2 relates, "and you can't do the level of detail that you can do in illustrator, but from the point of view of a user, there's like 10% of the people versus the 90% that really need a thing like Canva." In conjunction with a master's thesis showcasing a streamlined XR design process using affordable and off the shelf components, participant 3 mentions Syntacts as another tool extending accessible prototyping capabilities to designers. Describing the platform, participant 3 states, "Syntacts is open source. It's basically a haptics design tool like Photoshop." The examples discussed demonstrate that a trend toward democratization of tools can be leveraged by designers to lower the barrier of entry to and accelerate the prototyping phase of NAVI design. Participant 2 encapsulates the creative potential unleashed by such tools when stating, "we didn't wanna build haptics and stuff but we wanna build things that other people can build haptics with cause we are not haptic gods...let's democratize the tools."

In NAVIs the available sensory feedback modalities are limited to sound, speech and haptics. The latter, while occupying a limited role in mass digital media has been more commonly used in feedback for the blind and deaf communities. Participant 2 states, "the hardest thing about the haptics industry in particular is, that no one knows what the word haptic means. unless you're a gamer or you're blind." On a mass scale the integration of haptics as a cultural phenomenon is of more recent import resulting from experience generated through the use of ubiquitous technologies. Haptics on smartphones and watches, even laptops have quickly become familiar if not expected features of interaction with digital interfaces. The ability to describe such interaction, however, lags behind the experience of the same. Participant 2 describes his company's early approach to expanding the role of haptics stating, "our real dream was, you know, actually accessible navigation is kind of a Trojan horse, you know, it's just the way that people resonated with it, it was the market that really understood the value that we were giving." Participant 2 mentions the challenge in attempting to release a digital tool that would allow for customized haptic design when the majority are unfamiliar with haptics and its potential applications stating, "we just knew that no one would...so we started out with, Hey, here's a band that's gonna allow you to create haptics. But no one knew what haptic meant, so how would you create them?" Before developing a haptic design tool, participant 6 envisioned a future role for haptics stating, "active haptics is rarely part of everyday applications or your everyday life. And I was wondering a bit why that is so, and which advantages and opportunities could come when we would integrate vibro-tactile feedback. So vibration feedback in your desk, in your table, in your steering wheel, in your, I dunno, like everywhere in your environment." Participant 4 also seeing a more prominent role for haptics in the future maintains, "I think researchers and companies try to integrate the haptic sense for VR, and entertainment and immersion more and more."

In Table 4.12 participants 2, 3 and 6 discuss building tools or methods for streamlining the prototyping process. These tools include software for shaping haptic and audio feedback signals as well as hardware such as various actuators for testing this feedback and exploring optimal placement of wearables. The motivation for building prototyping tools arises from a need to simplify what is at present a complex and time-consuming design process. Access to such tools lowers the barrier of entry for designers new to haptic and audio feedback design, having little experience with coding or the hardware involved in deploying these feedback systems. The platform created by participant 2 also incorporates guidelines for feedback design ranging from physiological considerations to design strategies and the constraints set by sensory perception. Participants 6 and 4 envision a growing role for haptics in everyday applications. This is supported by an increased interest in such applications in research and in the market. Participant 2 views the NAVI market as an entry point for the expansion of the role of haptics into mainstream usage and notes that a descriptive language with which to describe the experience of haptics has been hitherto lacking.

Literature		**Interviews**	
		Participant 6	Haptics design tool for easier prototyping
		Participant 2	Canva vs Illustrator analogy for haptic design tool
		Participant 3	Syntacts haptic prototyping tool
		Participant 2	The challenge of introducing haptics is that descriptive language has not been fully integrated

		Participant 2	VI community already familiar with haptics, thus an easy point of entry
		Participant 6	Purpose in designing haptics prototyping tool was to integrate haptics into everyday applications
		Participant 4	Sees increasing role for haptics as driven by companies and research

Table 4.12 Democratization

5 Conclusion

In exploring literature about navigational aids for the blind and visually impaired, this research, in alignment with its initial questions of inquiry, has identified a set of essential considerarions useful to designers in achieving effective design solutions. To further define these considerations, the requirements framework proposed by Sharp et al. (2019) has been applied deductively to a thematic analysis of expert interviews. Interview data thus processed has been arranged under thematic categories including usability goals, user experience goals, functional requirements, data requirements, internal environmental requirements, physical environmental requirements and technical environmental requirements. Additional themes were applied to data analysis in order to capture trends and design approaches that can be leveraged by designers when designing NAVIs. In this section, research findings as they relate to the literature examined will be discussed. Based on findings that reflect the literature as well as findings discovered exclusively within the context of expert interviews, this research offers suggestions for arriving at better future NAVI designs.

For a designer, it is useful to first examine existing design solutions from the perspective of how the user experiences these in order to gain insights into what improvements can contribute to higher user acceptance. The reasons behind low adoption rates of NAVIs hitherto and as mentioned by Lloyd-Esenkaya et al. (2020) are at least in part attributable to factors of size, cost, discretion and aesthetic value. Participant 1 mentions the size of a NAVi as impacting the user's experience of comfort and safety as well as how they appear in the public eye when using a NAVI. Kuriakose et al. (2020) confirm this sentiment when stating that portability contributes to user acceptance and users prefer a device that provides for discretion in public settings. dos Santos et al. (2020) address the social stigma incurred by a user when donning an unsightly and bulky device in public. Finally, according to Messaoudi et al. (2022) the cost of a NAVI determines accessibility to users. Concurring with this last point, participant 2 mentions the economic challenges inherent to the BVI community in terms of costs that limit access to assistive technologies.

Usability goals describe how easily a user is able to learn and interact with a user interface and apply the advantages afforded by a device to daily activities. Insofar as it complicates initial interaction and immediate use and accessibility, extensive training times for a NAVI are viewed as potentially detrimental to user acceptance. Kuriakose et al. (2020) states that a reduction in training time leads to greater user acceptance. This is confirmed by participant 1 when stating that an easy to learn interface builds trust and can serve as a steppingstone to more complex interactions. Messaoudi et al.

(2022) also state that a UI should help users learn to operate a NAVI upon first use. Participants 1 and 3 propose that basic training options should be built into a UI to promote accessibility. Interview participants 1, 2 and 5, themselves involved with developing NAVIs, tended to approach the topic of customizability options for users conservatively, preferring rather to offer the best default settings possible. However, participant 1 agrress with Kuriakose et al. (2020) in regarding added customizability as a means for a user to mold the interface to suit their personal needs. Participant 1 notes that added customizability also implies an increase in complexity. Thus, designers must balance between complexity and customizability on one hand, and ease of accessibility on the other. An initial approach to a new UI may lean more firmly on ease of accessibility while a more long-term usage may necessitate added customizability.

Four trends and design approaches emerging from the literature and expert interviews and external to the requirements framework proposed by Sharp et al. (2019) affect the future trajectory of NAVI design as it applies to user experience and usability goals. The first is the trend toward miniaturization occurring as a biproduct of advances in technology. The second is the mass adoption into daily use of ubiquitous technologies such as tablets and smart phones. The third is the intuitive design approach which entails deploying familiar formats when designing to ease the user adaptation to a new interface. The fourth theme is the inclusive design approach which allows for design solutions to be scaled up for a larger target audience while factoring in the needs and accessibility concerns of disadvantaged groups.

In designing with user experience in mind, designers of NAVIs have historically been constrained by existing technologies when considering for size and portability options in a NAVI. More recently, however, developments in the technical environment have led to a trend towards miniaturization of components crucial to NAVI design. This has had positive implications on cost factors of components. Real & Araujo (2019) note that cost and size of microprocessors and sensors has led to more wearable options in NAVIs contributing to more portable and discreet solutions for BVI users. Participants 1, 2 and 4 all describe the benefits that miniaturization has had in terms of cost, size and portability in the context of their own NAVI projects. Participant 2 provides additional details on how the simplification and reduction of components allowed for even further decreases in size of the end product that contributed in turn to lower costs. Thus, designers of NAVIs should take advantage not only of the gradual miniaturization of technologies and components but they should aspire to factor user experience goals into their iterative process, further reducing size, bulk and costs of NAVIs and NAVI-related wearables.

NAVIs that operate through ubiquitous technologies such as smartphones or tablets enhance both user experience and usability. In terms of user experience, due to widespread use, smartphones are more affordable than a specialized device designed for a niche target user group would be. Widespread use extends ever increasingly to the BVI community as facilitated by BVI-friendly features in smartphones and tablets that enhance accessibility. Thus, a smartphone-based NAVI app supported by a preexisting personal technology like a smartphone comes at little additional cost to the user. In addition, Tyagi et al. (2021) state that the compatibility of a NAVI with preexisting technologies will increase everyday use. This compatibility not only enhances user experience by virtue of the convenience it affords the user but also adds to usability because of the user's familiarity with the interface through daily use. Payyanur (2019) notes that familiarity reduces the learning curve when adapting to a new interface. This implies that NAVI apps used through an already familiar smartphone interface are easier to learn thereby increasing usability. This intuitive design approach has been previously applied to the design of NAVI devices by using a format familiar to the BVI user group to enhance graspability upon first use. Ahlmark (2022) describes the application of this intuitive design approach when basing his own NAVI solution upon the commonly used white cane. However, smartphones, aside from offering a familiar format to users through daily use, represent a host of integrated capabilities that can be combined and leveraged for better NAVI designs. Participants 1, 3 and 4 mention the usefulness of leveraging user familiarity with preexisting haptic feedback options in smartphones when designing new NAVI feedback languages to increase accessibility. Participant 5 mentions deployment of GPS and open map data in his NAVi app. Participants also mention advances in smartphone cameras which allow for more precise depth sensing of the physical environment. Thus, in the integrated capabilities embedded in smartphones and tablets in conjunction with ubiquitous use and familiarity provide designers of NAVIs with a formidable arsenal that supports better NAVi design.

Examples of the inclusive design approach intended to benefit the BVI community in the context of navigation in public spaces are visible in the forms of tactile paving and sound location beacons on metro platforms. The inclusive design approach aims to design for a wider target user group while considering the needs of smaller disadvantaged user groups. NAVIs have previously been designed for a niche user group. Within this context and in fulfilling the functional aims of not only navigation but landmark description and obstacle avoidance, features fine-tuned over years of NAVI development are also scaled to serve the needs of wider audiences. Lloyd-Esenkaya et al. (2020) also suggests that the benefits achieved in deploying feedback methods in NAVIs for the VI user group can be scaled for wider usage. Participant 2 describes how scaling features of a NAVI to the larger tourism industry allowed for the benefits of years of development to be applied to a wider target user group. As a result of this strategy and its success, the NAVI was able to be offered to the BVI community for free. Participant 5 in discussing business strategy, notes the practicality of making an interface that benefits all and also considers the VI community in its design. However, participant 5 also mentions how working with the niche BVI community facilitated the development of features and capabilities that might not have been considered when designing for a larger audience. Thus, it can be concluded that two avenues are available to designers when designing navigational solutions for the BVI community. Designing specifically for the BVI community however facilitates a more focused development process, the fruits of which can then be scaled to benefit the many.

Assessing the functional requirements for a NAVI design involves continued contact with the BVI user group and considering the specific use case that will inform that design. In the literature, testing of a NAVI prototype with the user group is described but assessments of user needs and formulation of a use case scenario based on interviews or surveys is rare. In research detailing the development of individual NAVIs, a focus on aspects of engineering is more commonplace. Swobodzinski & Parker (2019) conduct focus groups with BVI users to identify gaps in user experience as they apply to NAVIs already in use. This is helpful in identifying where future designs could be improved but does not address why these gaps between user needs and functional requirements in NAVI designs are so prevalent. Sharp et al. (2019) notes that involving users in the problem definition and continued iteration process facilitates better design solutions. As interview participants in this research were selected in part based on previous design experience, it is unsurprising that design methods aiming to align a design solution with user needs are more readily described. When asked how one would begin the NAVI design process, participant 4 advises to Involve users in problem definition early on looking at use context and tasks to fulfill. In addition, participant 4 recommends conducting interviews to learn how BVI users use navigational aids. Participant 3 suggest that designers empathize with user's needs and explore the intended environment in which a NAVI is to be used to gain insights. Continually updating his in the market NAVI application, participant 5 describes ongoing contact with and feedback from beta-testers. Participant 5 also describes how considering the use case of an individual user from Mexico allowed for a system wide improvement in functionality to his NAVI application. This improvement introduced the option of using a simple music controller, allowing BVI users to conceal their smartphones thereby enhancing user experience in the perception of safety and increasing usability with added functionality. Thus, communication and ongoing inclusion of users in the design process situates a designer to receive unique and game-changing insights that will contribute to more effective design solutions.

When considering data requirements in designing a feedback language for a NAVI, examining environmental requirements helps designers to understand the constraints that limit the expression of that feedback language. Three thematic categories of environmental requirements have been used in this research. These are internal environmental requirements describing neuro cognitive and physiological constraints, physical environmental requirements describing the outdoor or indoor surroundings within which the user will use the NAVI and technical environmental requirements which describe the currently available technologies to be used in the NAVI. Each individual environmental requirement can be seen to temper the expression of the others in fulfilling the goal of providing feedback that aligns with the functional requirements as determined by contact with the user. According to Sharp et al. (2019) viewing design problems through the requirements lens allows designers to capture details and considerations that might otherwise be overlooked in the definition phase of the design process.

In assessing internal environmental requirements crucial to designing effective NAVI feedback languages, the limitations imposed by sensory bandwidth are mentioned in the literature and by interview participants. The bandwidth of sight is considerably higher than that of the other senses. According to Kristjánsson et al. (2016) this constrains the amount and quality of information that can be communicated through audio or haptic means. Participant 7 notes that Information is inevitably lost when translating from the visual to the auditory. Participant 1 confirms this in claiming that cross modal sensory translations are only part way which leaves designers of feedback to consider, within the context of decreased bandwidth, which information is absolutely essential to convey? Kuriakose et al. (2020) suggest that in addition to including only necessary information, feedback should consider proper timing in conveying that information. Timing is important because as Ahlmark (2022) states, a sighted individual gets environmental information at a glance, while a blind or visually impaired individual maps their surroundings in steps. Also, in terms of the timing of feedback, audio and haptic means of feedback differ. Participant 2 describes sound as linear, meaning that a recipient of audio feedback needs to wait to the end of the transmission of the signal in order to process that signal. This is particularly relevant for descriptive speech feedback methods. Haptic feedback in contrast is more immediate. Participant 2 recommends that designers should optimize feedback for what the particular type of feedback is best at conveying. Thus, to develop more effective feedback languages, designers of NAVIs should consider what is possible to convey through a given sensory channel and how bandwidth constrains the amount of information that can be processed by a user. Also the proper timing of feedback is crucial for building a useful and safe experience for the user in a dynamic environment.

Advances in the technical environmental domain support the deployment of feedback methods which facilitate building a picture of the user's physical environment in steps. In contrast to actively scanning the environment for objects and obstacles, a BVI user is better served by updates of relevant places of interest as the user moves through that environment. Aiordăchioae et al. (2020) note that providing this type of passive situational awareness is possible through depth sensing camera technologies as they currently exist in smartphones and wearables. In addition, Kuriakose et al. (2020) and Ojala (2018) mention that computer vision and deep learning methods are ideal for obstacle detection and real time navigation. Participant 3 also mentions that camera vision and depth sensing provide a more in-depth depiction of a BVI user's surroundings. Participant 1 notes that AI camera-based technologies provide users with the ability to more immediately map and recognize elements of their surroundings through descriptive speech feedback. Participant 5 describes the active expansion of the library of speech descriptions for obstacles and places of interest for providing better situational awareness to users. With such an ever-expanding library, it is important to mention the inclusion of customization filters within participant 5's NAVI interface to allow users to choose what information is relevant to convey. Thus, customization can also be used to manage increased complexity and support an individual user's preferences in tailoring their experience to suit their needs. Designers of NAVIs should leverage newly developed capabilities particularly as they exist within ubiquitous technologies when designing feedback methods that help users to build more cohesive and dynamic descriptions of their environment.

Overall, when considering feedback for NAVIs, care must be taken not to overload any one sensory channel. Findings from expert interviews concur with sources from the literature in recommending a multimodal feedback language for NAVIs. The reasons for this are as Kuriakose et al. (2020) state, that multimodal feedback helps the user to avoid sensory overload and provides for flexibility in varied environments. Participant 1 states that the danger of sensory overload is especially relevant in complex or noisy environments and recommends distributing information across multiple sensory channels as a preventative measure. Participant 5 notes that in providing a feedback solution, it is important not to occlude a BVI user's sense of hearing as naturally occurring audio information from the surroundings are also crucial for assessing proximity to objects. A logical alternative to audio feedback in noisy environments is haptic feedback. Patil et al. (2018) note that haptic feedback does not occlude hearing and as such is ideal for NAVI applications. However, due to the lower bandwidth of touch, designers should moderate the amount and intensity of haptic feedback as compared with audio feedback. Participants 4 and 6 mention that haptic feedback can easily overwhelm a user's senses. Participant 6 recommends that the amount of haptic feedback should align with the intended application. As previously mentioned, designers need to consider the relative bandwidths of sensory channels when designing for effective feedback. Audio feedback can communicate more about the user's environment but can also occlude information from the natural surroundings. Haptic feedback applied in a multimodal feedback format can provide flexibility to the user as they navigate from one environment to another but its lower bandwidth relative to sound necessitates that it be used with frugality. Ultimately, a multimodal approach to feedback methods lends flexibility to a NAVI design and aligns with the complexity of the user's daily needs as they navigate through varied physical environments.

Specific feedback methods described in the literature reviewed are confirmed by interview participants. Notable among these are feedback facilitating directional orientation and corrective feedback deployed for communicating when a user has crossed a boundary. Lock et al. (2023) describe a NAVI using spatialized sound where variations in pitch, gain and panning correspond to the height, horizontal distance and angular orientation of an obstacle. Participants 5 and 7 also describe the use of stereophonic sound in communicating directional information. Participant 5 mentions the use of descriptive speech using clock face orientation within the context of his NAVI application. Participant 5 also mentions the use of a haptic belt wearable with actuators distributed radially for intuitive directional correlation. Velázquez et al. (2018) also describes directional haptic feedback but administered through a shoe insert wearable. In contrast to the latter, Participant 2 describes navigational guidance through haptic corrective feedback whereby deviation from a predetermined route elicits a haptic nudge. Moesgen et al. (2022) explore corrective haptic feedback in combination with visual feedback to guide the limb motion of stroke victims and to inform when a threshold has been crossed. Participant 5 describes using sound cues to inform BVI users that an obstacle or object is directly ahead. In designing effective NAVI feedback, designers can make use of directional and corrective feedback and apply these in a multimodal distribution that best suits the information to be communicated.

Interviews with XR designers yielded additional insights into feedback design that may assist NAVI designers in expanding the available repertoire of feedback vocabulary and enhancing the perception of realness that the user attributes to environmental stimuli as artificially represented by a feedback language. Participants 3 and 6 describe how using coincidental audio cues to shape haptics can help increase feedback vocabulary. This method of coincidental feedback design is not mentioned in the literature on NAVIs reviewed in this research. In addition, and in line with the idea of spatiotemporal congruence as described by Lloyd-Esenkaya et al. (2020), the temporal coincidence of haptic and audio cues contributes to the user's perception of realness. According to Kristjánsson et al. (2016) this sense of realness is further reinforced by the user's repeated motor activity in conjunction with feedback. Though the goals of VR and AR particularly as they relate to the context of gaming may be different than that of NAVIs, the idea of immersion as facilitated through artificial multimodal feedback methods is applicable to NAVI design. This is especially true as both domains aim to optimize feedback to conform to the way in which humans process sensory stimuli. Thus, further investigation into explorations and applications of feedback as they are occurring within the domain of XR design may help designers of NAVIs in developing more effective feedback methods.

Expert interviews with XR designers also revealed insights into the prototyping process and prototyping tools that will lower the barrier of entry for designers of audio and haptic feedback systems in wearable applications. Descriptions of experiences with prototyping were gathered under the theme of trends and imply a move towards democratization of prototyping tools. Previously, the process of testing a NAVI prototype involved prior knowledge of electronics and coding. This has been a deterrent for designers aspiring to work with design of feedback systems in wearables. However, toolkits which combine ready to use actuators and sensors with parametric software for haptic and audio feedback design as described by interview participants will streamline the design and prototyping process considerably. This is especially important as the testing and fine-tuning phase for feedback systems is already time consuming and must factor in optimal placement on the body (for haptic applications), and user testing. Participants 2, 3 and 6 describe developing such prototyping tools particularly for haptic feedback design. Thus, with these new tools at their disposal, designers of NAVIs can devote more time to fine-tuning and testing. This allows more time for designers to focus upon user experience and usability, factors which will strongly influence adoption of a NAVI solution by a BVI user.

6 Discussion

Through an initial literature review, this research sought to form a wholistic understanding of NAVIs and the considerations which inform designers new to the NAVI design process. In this discovery phase the complexity of currently available NAVI solutions was revealed. The challenge in confronting such complexity was to discern patterns of uniformity that applied to all of the solutions explored. After literature review, patterns of repeated topics emerged that helped to inform the expert interview process. The extent to which the interview questions based on these topics influenced what data was obtained must be acknowledged. Following the first expert interview, one way to circumvent this shortcoming was to adopt a freeform approach to subsequent interviews allowing for interview participants to pursue avenues of discussion that better reflected their experience and expertise on the topic matter. A set of predetermined topics rather than questions were henceforth used to loosely guide interviews. Through this approach unanticipated information not appearing in the literature was obtained.

To organize the interview data, the requirements framework proposed by Sharp et al. (2019) was applied through thematic analysis. Codes were applied to quotes from interviews which were organized under themes reflecting requirements necessary for NAVI design. The first organization of codes into thematic categories revealed gaps in the data gathered. This was particularly evident in the theme of functional requirements or the intended function or tasks the NAVI is meant to perform for the user. As members of the BVI user group were not interviewed to obtain this data, details of contact with the user group to assess user needs was exclusively obtained through the experts interviewed. Codes describing contact with the user group and use case specifics were initially grouped under the theme of usability goals. Later, the value of the data contained in these codes was recognized as they reveal the designers' approach to inclusion of the user into the design process. Thus, these codes were moved to the functional requirements theme. In the literature review, Swobodzinski & Parker (2019) describe conducting focus groups with BVI users to discuss and evaluate NAVIs. The insights revealed focus primarily on deficits in user experience and usability. For this research however, a focus on the designer's journey was deemed more important and thus the insights gathered through expert interviews into how designers design for fulfilling functional goals sufficed for this purpose.

Another theme that when initially applied failed to capture the full range of the processed interview data was technical environmental requirements. The technical environment is the most dynamic and rapidly changing environment and so a temporal element must be considered, involving possible future trajectories based on that current environment. This stands in contrast to the internal cognitive environment or the physical environment which are relatively static in their features and constraints. The theme of trends was then created to more accurately reflect the momentum and impact on the future of NAVI design. Codes gathered under the theme of trends described both technological aspects and cultural phenomena related to technologies. In reorganizing, the theme of technical environmental requirements was assigned to codes such as wearables, tags and necessary components while trends captured technologically related topics with wider social implications such as miniaturization, ubiquitous technologies and democratization of design tools.

Aside from trends, a second theme outside of the requirements framework was applied in organizing interview data to capture design approaches and strategies available to designers of NAVIs. Design approaches as a theme includes strategies such as inclusive and intuitive design as well as elements of the iteration process such as testing, prototyping and cross disciplinary collaboration. As expert interview participants represented NAVI designers as well as XR designers, valuable information about the design process was revealed. The contrast between the two expert participant categories was also evident in the latter group's focus on streamlining the prototyping process. This focus, further explored, uncovered tools that will lower the barrier for designers new to prototyping feedback methods for NAVIs and beyond.

In this research, the complexity of data obtained from both literature review and expert interviews posed a significant challenge in terms of narrowing the scope of what was to be studied. One way to address this complexity while still adhering to the requirements framework was to subordinate all themes under the primary theme of data requirements. The rationale supporting this organization lies in the fact of NAVIs being fundamentally communicative in nature. Thus, all other goals and requirements support the goal of designing a feedback language that communicates a representation of the physical environment through technological means in alignment with the performance needs as defined by contact with the user group. The usability and efficacy of a feedback system will also directly impact the adoption of a NAVI and its daily use. User experience represents more superficial concerns of the user upon first introduction to a NAVI including appearance and cost. These concerns may seem unrelated to data requirements but in fact represent a first threshold that must be crossed for a user to integrate a NAVI into daily use. Moreover, the seemingly aesthetic consideration regarding placement of a NAVI wearable is inextricably interwoven with how feedback, particularly haptic feedback is effectively transmitted. However, for the sake of simplicity, overlap between requirement themes has not been emphasized in this research.

This research has focused upon discovering and defining the requirements that designers new to the field must consider when approaching the design of NAVIs. Despite data requirements, specifically feedback systems occupying central importance in this research, a more superficial approach to understanding these systems has been taken to allow for all relevant requirements to be explored. In future research, a more specific focus on optimizing multimodal feedback systems and languages for widespread use could be explored. This could address the challenges of reaching common understandings or a standardized feedback vocabulary on a global scale. Integration of diverse modes of information transmission outside the dominant modality of sight may contribute to a richer more flexible human communicative experience particularly as our relationship with ubiquitous technologies matures.

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APPENDIX 1
Invitation to Participate

Dear XXX,

My name is Tomi Monahan and I am an undergraduate in the Bachelor's Programme in Design, Bachelor and Master of Arts (3 yrs + 2 yrs) at Aalto University. I am working on a research project under the supervision of Prof. Oscar Person.

I am writing to you today to invite you to participate in a study entitled:

Navigational Aids for the Visually Impaired
Identifying the Requirements for Effective Design

This study aims to better understand the considerations that inform designers of feedback systems in navigational aids for the blind and visually impaired. The following research questions serve as the basis for this research:

Why are adoption rates for assistive navigational technologies low among the visually impaired?

What are the essential requirements for designing effective assistive navigational aids for the blind and visually impaired?

How can these requirements be further defined to help designers of assistive technologies arrive at more effective feedback systems?

The study involves a 45 to 60 minute interview that will take place on Zoom or GoogleMeet. With your consent, the interview will be audio-recorded and transcribed. Upon transcription, the interview will be anonymized and the audio recording will be deleted.

If you would like to participate in this research project or have any questions about the research, please feel free to contact me at:

Email: tomi.monahan@aalto.fi or,
Cell: +358 442384029

Sincerely,

Tomi Monahan

APPENDIX 2
Informed consent table

Aalto University
School of Arts, Design
and Architecture

Consent to Participate

Consent to Participate in a Research on Sensory Substitution and Assistive Technologies for the Visually Impaired

I,_______ have been clearly informed on the purpose and procedures of the research led by Tomi Monahan at Aalto University School of Arts, Design and Architecture, Espoo, Bachelor's Program in Design and have shown interest to participate in the studies developed by the student cited above. I am aware and understand the contents of the research and how my participation will occur.

This research includes an interview on the topic of navigational assistive technologies for the blind and visually impaired

I agree to participate

Date and Place: February 8, 2023 at Aalto University

____
Signature of Participant

____
Signature of Researcher

Contact Information: Tomi Monahan tomi.monahan@aalto.fi

Tel. +358 442384029

I volunteer to participate in the studies. I may choose to rescind or abort my participation in the studies at any time during the studies, by informing the student cited above. Rescinding or aborting my participation will not affect my position at any point in time. I may also revoke this consent to participate in the study, in which case information pertaining to me will not be used in the studies. Research results pertaining to me may be used in scientific reporting (e.g. publications).

This study follows the responsible conduct of research, legislation and guidelines available at http://www.tenk.fi/en/resposible-conductresearch-guidelines

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Student in New Media

APPENDIX 3

Guiding Questions for Interviews

Topic	**Question**
Defining Parameters	What are the main parameters of sensory substitution design and how would you prioritize or balance these? Where does one begin when thinking of developing SSD?
Unimodal vs Multimodal Feedback	What are your thoughts on unimodal vs multimodal means of conveying information? When might you use one over the other?
Vibrotactile vs Audio	Are there advantages to using one form of feedback over another?
Intuitive First Use vs Training	How can an assistive technology that's easy for the user to grasp upon first use be compared with one requiring a training period? When is one or the other a good idea?
Neurosciences	How have understandings emerging from the cognitive sciences informed the way you develop feedback systems?
Sensory Overload	When considering communicating a representation of the environment to the user, how much information is too much?
Low Adoption Rates by the Blind and Visually Impaired	What might be the reason behind the low adoption rates of assistive technologies among the Blind and Visually impaired. Has the situation changed? How? What are some ways that adoption rates might be increased?
Academia vs Marketplace	How do academia and the marketplace differ in their handling of NAVI projects?
Ubiquitous Technologies	What is the role of ubiquitous technology in relation to the current NAVI market?
HCI and Fine-Tuning in the Test Phase	How has HCI played a role in the way that you develop your projects?
Heterogeneity of Target User Group	How does the heterogeneity of the Blind and Visually Impaired

	community complicate or inform your process when testing a prototype for instance?
Navigation and Obstacle Avoidance.	In terms of vibrotactile or haptic feedback, what would you consider to be the best way to provide a visually impaired person with information about navigation and obstacle avoidance? Is there at this point a standard or guidelines which a developer or designer could follow?
The Role of Landmarks in conveying a more comprehensive picture of the environment	How do landmarks figure into NAVI design? How would this type of information be best communicated?
Recent Innovations	What are some scientific/technological advances or even game changers that have emerged in recent years?
Directional Force Feedback, Repulsion/Attraction, Saltatory	Which types of vibrotactile feedback do you consider to be most useful in NAVI design?

Appendix 4 - Coded Interview Excerpt

Interview Transcript	**Codes & Explanations**
(Recording mistakenly started a few minutes after the start of interview)...I thought a lot about this kind of thing you have read actually The process behind my dissertation was back then at least what was out there was really trying to convey the visual information by complex auditory signals. So there were apps and also some device trying to translate the visual information by the pixels in the image through auditory signals and there were also these devices you know you can have on the tongue to have a tactile response and some people were very proficient with other things but....the tricky thing to remember here is the specific application will affect the design a lot, so in navigation aids we have so many other factors to take into account you know the space around us	**Feedback Language** (conveying visual information with complex auditory signals, tactile...) **Use Case Specific** (specific application will affect design)(navigation in complex environments) **Bandwidth Limitations** (visual channel very rich, lots of information quickly so how to convey?) **Sensory Overload** (complexity of environment and difficulty of communicating visual information) **Testing/Exploration** (what parameters to use to filter information)

out and about in the city you have to hear the cars and what have you. So in a very complex environment you cannot just overload any sense in that kind of application. So this is the thing that I find most tricky is that the visual information is so rich, the bandwidth is so high in that channel. So you get a lot of information very quickly and this is the tricky issue to convey with other senses so you have to filter and what parameters can you use to filter the information. Yeah, this requires I believe some, well, a lot of exploration and testing to find out	
R	
I remember you mentioning in your thesis the idea of a fingerprint or a landmark in providing a context for a visually impaired person to navigate a given environment and that constructing a fuller picture of that environment requires movement if you're using the haptic approach in providing feedback. So is there a way an ideal way to, let's say you're presenting someone with an introductory SS device, is there an ideal way to present that information without having to undergo training?	
P1	
A very good question. Wow, I have to think back because you know I've been absent from this kind of thing for a long time being in the industry I haven't really thought about these things lately but what I would say is the tricky thing here is that when you try to substitute a sense, you're only doing this part way so we can substitute a set of stimuli from one sense to another but that doesn't get the whole world experience across. You can translate a pixel into an audio signal or haptic feedback but that doesn't work	**Bandwidth Limitations** (sight has greater bandwidth than other senses, translation of environmental information always incomplete) **Intuitive Approach** (utilize naturally occurring spatial properties, analogue btw sight and touch) **Feedback Type** (haptic, because of spatial property shared with sight)

in the same way…you are using a sense, you are used to a sense in a specific way so I believe it's tricky to do this kind of thing just immediately because of those reasons so actually…ok if we deal with haptics, there's a natural correlation there with the visual space and this is what we try to use in my thesis and so that is, we move our hands or fingers in the physical space so we have a sort of correspondence which you don't have for instance if you're doing this in audio but ok so we're doing this in haptics, so I would say try to utilize this spatial property because there's another way of going with these vibrations and so on just trying to map the space out as a shape but if you can utilize the natural spatial properties that we have, that would be more intuitive because we're used to that.	
R	
I found your LaserNavigator kind of fascinating because you were using the the batural space between the body and the device and using that as a way to create additional information about how the device measures distance to an external object.	
P1	
Exactly so there the body itself, you as the user, you are involved in actually giving this information so to say so you are a part of it in that sense and even, we did this before the LaserNavigator, we did the sighted wheelchair, where we had a haptic robot, this kind of interface where you have…you probably saw it in the…	
R	
Yeah.	
P1	

Yeah. So there you could feel actual resistance, you could feel a bump or actually a wall, some physical wall when you rode this thing around and it involves using the idea of this natural space, so, I believe well this was at least the intention from the get-go was that this should be more intuitive than say trying to convey something like a braille display or something like a tactile surface.	**Intuitive Approach** (feeling a bump or virtual wall)
R	
Yeah it's interesting...	
P1	
I still believe in that idea although I did not get all the way in that project because of the richness of information that's out there in the visual domain.	**Bandwidth Limitations** (richness of sense of vision)
R	
It seems like from a design point of view the idea that you're taking an already existing device that's used like the white cane and sort of extending its reach digitally is very intuitive, easy to approach for the user group.	
P1	
Yes. I would say that the cane is a good analogy here because many visually impaired or blind people use that. Even if you are not, you could easily grasp the concept of the cane. So yeah, try to utilize that as much as possible, it could be very helpful because really, I didn't, we didn't study that idea as a separate thing. We had user trials and I could sort of think that yeah, this is probably true, ok they could use the device and they could understand how it worked very quickly but still it was different enough from anything else that it wasn't easy overall.	**Intuitive Approach** (white cane as familiar to user group) **Testing/Exploration** (although analogous to existing device, still some difficulty in adapting)

Appendix 5 - Table of Themes & Codes

Theme	Code

Internal Environmental Requirements (Neurocognitive Features)	Bandwidth Limitations
	Sensory Overload
	Sensory Substitution
	Sensory Perception
	Immersion/Multi-sensory Integration
	Skin Receptors
	Tactile Phenomenon
Usability Goals	Accessibility of Interface
	User Preferences/Customizability
	Need for Training
User Experience Goals	Low Adoption Rate
Funcional Requirements	Contact with User Group
	Use Case Specific
Design Tools	Inclusive Design/Scale
	Intuitive Design
	Testing/Exploration
	Cross-Disciplinary Collaboration
	Prototyping
Data Requirements	Multimodal Feedback
	Feedback Type
	Feedback Language
Physical Environmental Requirements	Source/Input
Technical Environmental Requirements	Necessary Components
	Wearables
	Smartphones/Tablets
	Bone Conduction Headphones
	Tags
Developments & Trends	Advances in Technology
	Ubiquitous Technology
	Miniaturization
	Integration of Haptics (as a cultural phenomenon)
	Standardization
	Democratization
	Haptician/Haptics

Appendix 6 - Sample of Codebook

Example Quotes	Description	Code
So there is this idea where you can have feedback and	Multimodal feedback methods in relation to	**Multimodal Feed-back**

I'm thinking, what would be interesting would be to combine, let's say we have a haptic system to get a feel for the environment in some way and then we could have auditory feed-back , not in like to try to replicate a sense but maybe a voice that tells you things. (Interview	NAVIs are mentioned or described.	
So maybe today the device would be smaller, sim-pler, just focused on get-ting data from the envi-ronment, and then you would have a combination of maybe specialized hardware for the feedback like a haptic gadget or so on, or maybe use a watch or a belt or whatever to convey....again this is the idea of multimodal feed-back so you could have speech and haptics and so on. (Interview		
I would play with audio to do, to divide, define cate-gories and haptic cues to define patterns left to right. Stuff like that. (In-terview		
Maybe in combination, like if you use it for Google Maps Yeah. And you walk straight and then Google Maps tries to let you walk straight and then it says, okay, now to the left, and then, you know, kind of how much to the left		

because of the buzzing. (Interview		
So in that sense it was very context dependent on the task, and the context was how to guide stroke patients with haptics as an additional modality with the visuals they already saw in the VR game or maybe even audio guiding them. (Interview		
Also interestingly with the vr, because you don't really see your torso so it would be also interesting or I guess beneficial to use vibration feedback on the shoulder because you usually don't look at your shoulder in vr, so to have this notification-like modality if they would make mistakes with the shoulder. (Interview		
But, I have also found some research articles, big team of professors, fancy team doing research, how to implement assistive technology and the results then, say that, you need to, speak very, few sentences and have sound effects. (Interview		
So you'll hear obstacle sound that is, sound is like ‘blonk’. If you hit, It's out, out sound, and then you hear, gate five meters. (Interview		
If the sound is abstract in a way that mine was, and		

in a way that voices, although voice can be understood better in terms of like, if you can make, I guess you can even describe it to a blind person, like what the voice does internally, and then can, in the brain kind of cognitively. (Interview		