MOUNT HOLYOKE COLLEGE SENIOR THESIS

"Who's There?": Designing Sensor-Aided Wearable Assistive Technology for The Visually Impaired

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Abstract

Approximately 4% of the world's population is visually impaired, with 65% of them over age 50; and an estimate of 90% of them living in low and middle-income countries. While these numbers are shocking, the bigger challenge is the reduced confidence and life satisfaction that the visually impaired experience as a result of loss in independence and diminished sociability. This project tries to mitigate the problem of dependence using low-cost, intuitive, sensor-aided assistive technology. Interacting with visually-impaired users, we identified 3 specific problems: difficulty recognizing those in their surroundings; inability to proactively greet persons entering their social space; and not knowing if the person they are interacting with is within hearing range as they move around. While previous research in assistive technology for the blind has largely focused on enabling smoother navigation, there has been less focus on improving their social interactions.

We employ a user-centered design approach and think-aloud protocol to gain insight into the user's cognitive processes, comfort level and feelings while they are interacting with the device and performing various structured social interaction tasks. Furthermore, we use standard psychological instruments to measure changes in sociability, independence and technological comfort as the users use the device.

We developed two distinct prototypes with several iterations of the design-thinking process. The first relied on a smart-phone to notify the user. While it performed the tasks, it was too cognitively overwhelming, frustrating and exhausting for a blind user because of the phone's many notifications. Therefore, it was an ineffective way of augmenting their perception.

Our second prototype, and current solution, is threefold: building a smart environment; designing a single-purpose, wearable bracelet with sonifications and vibro-tactile communication; and creating a novel audio-haptic user interface. We evaluated this device and chose it as our current solution because it is a low-cost, low-energy, easy-to-use, intuitive device that was successfully used by potential users to identify and place potential interactors in their surroundings during usability testing and user feedback sessions.

This project presents a foundation for designing more intuitive audio-haptic interfaces and devices for not only visually-impaired, but also for aging populations and sighted individuals. It proposes future research avenues overcoming current limitations, exploring long-term effects of the assistive device on the user's well-being, and enabling customization to an individual user's needs.

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1 Introduction

1.1 The Problem

The reduced ability to see to a level that cannot be cured by standard corrective measures such as glasses, contact lenses, medicine, or surgery is called visual impairment. It interferes with a person's ability to perform everyday activities at varying levels. While blindness is a severe vision impairment, legal blindness is defined as vision with best correction in the better eye worse than or equal to 20/200 or a visual field of less than 20 degrees in diameter. [2]

A study done by the World Health Organization [1] reports about 285 million people to be visually impaired worldwide: 39 million of whom are blind and 246 million have low vision. Visual impairment is one of the most common problems that arises as we age. About 65 % of all people who are visually impaired are aged 50 and older. The aged visually impaired make up approximately 2% of the world's population. With an increasing elderly population in many countries, more people will be at risk of visual impairment due to chronic eye diseases and aging processes. [1]

While these numbers are shocking, what is even more upsetting is that visual impairment has been shown to be associated with significant loss of independence, reduced sociability and decrease in life satisfaction. [12,13, 17]. In an extensive research review of the quantitative studies of older people published between 1980 and the summer of 2001, Burmedi et al. reported that vision loss was associated with depression, poorer quality of life, and reduced social activity. Furthermore, it stated the importance of social support in preventing this, with family and friends being important providers of support [12].

Due to the prevalence of vision loss and its significant reduction in psychosocial well-being, it is imperative that we come up with a solution that enables visually impaired users to engage in social interactions independently to counteract such negative effects. Interacting with potential users and their family and friends to further understand the problem, we realized that the major concerns in engaging in social interactions for the blind user independently are that: (a) they cannot recognize who is in their surroundings, (b) if the interactors are moving then not knowing whether they are still in the room or have left it and, (c) not knowing who is entering their interpersonal space so that they can proactively greet them. Therefore, our goal in this research project is to design an assistive device for the visually impaired that helps them identify persons in their surroundings such that it hopefully increases their sociability and independence.

1.2 Our Approach

Few technologists have attempted to solve this problem because it is hard to come up with an efficient technical solution that organically augments the mental and social schema already learnt by the user. A major challenge is to not block or replace any pre-existing information processing streams already learnt by the visually impaired user as they adapted to this loss. In order to attempt to solve this problem, we, as technologists, must also understand the cognitive processes involved in how the visually impaired create mental maps of their surroundings using cues other than sight. Additionally, we must understand how humans interact with different people in their social space, how we recognize and adapt our interaction behavior based on who it is and how far away they are from us. Only after we understand the cognitive and social sides to this issue can we successfully create technology that organically augments the user's experience and is easily learnt and integrated into their daily lives. This problem has been a hard one to solve because it is not only a technical problem but also a cognitive and social problem.

In this project, we approached this socio-technical problem by employing a systems approach to understand cognitive, social and technical sides and then built a focused solution using a user-centered design approach. First, we researched the neuro-cognitive background of visual impairment and adaptation and then we looked at the technological background in creating assistive technology, and multi-sensory user interfaces. As part of the user-centered design approach, surveys and semi-structured interviews were used to understand and identify explicit user needs and wants. We also employed the Think-Aloud Protocol [47] to evaluate user feedback during usability testing and gain insight into the user's cognitive processes, comfort levels and feelings while they interact with the device and performing various structured tasks. We audio and video recorded these interactions during usability testing, so that we could go back and refer to what the users did, how they reacted, what they were comfortable with and what made them anxious. In an effort to understand and quantify the user experience more thoroughly, we also collected data from standard psychological scales to measure participants' sociability, and technological comfort before and after device use. Additionally, we used a rubric to track the users' independence in engaging in social tasks while using the device.

1.3 Prototyping Solutions

Using the iterative user-centered design process, we designed 2 distinct prototypes for the solution. The first prototype was based on the iPhone. This first prototype application enabled the visually-impaired user to identify and place people in their surroundings. It informed the user of their proximity to a potential interactor through designated speech notifications, sonifications and vibro-tactile haptic notifications. These notifications varied in amplitude and frequency to signal significant changes in proximity. The farther away the potential interactor, the fainter the sonifications and vibrational patterns. However, as they got closer the notifications would increase in both amplitude and frequency. This application can detect when people were in *motion* or *still*, keep track of multiple people at the same time, and how close they are (either immediate, near, far or unknown).

However, usability analysis and user-feedback we received helped us realize that using an iPhone can be cognitively overwhelming, frustrating and exhausting for a blind user because of the multitude of notifications an iPhone provides us with. Therefore, this is an unintuitive and ineffective way of augmenting the user's perception. Moreover, as we interacted with potential users and explored devices they interacted with successfully on a daily basis, we realized that these devices are often single-purpose and used a simple set of gestures to convey one piece of information. Therefore, moving forward for the second prototype, we designed a single-purpose wearable device that is built on a low-cost, low-power system and notifies users using not only sonifications, and speech notifications but also haptic signals to augment the information a user gets about their surroundings.

Our second prototype, and current solution, is threefold: building a smart environment; designing a wearable bracelet with sonifications and vibro-tactile communication; and creating a novel audio-haptic user interface. The wireless wearable bracelet sounds uniquely designed sonifications and vibrates appropriately to help users not only identify persons, but also help determine their proximity. With this audio-haptic user interface, we hope to intercept and augment the neural processing pathways in the brain that usually process visual cues to determine what they are (ventral pathway) and where they are in space (dorsal pathway) with auditory and tactile cues instead. This should hopefully enable the visually-impaired user to perceive their surroundings. We also measure changes in independence and sociability during our survey of user needs and usability testing stages as a pre-post experiment.

1.4 Contributions

This project shows us a way that we can overcome the challenges of socio-technical problems to contribute something significant to not only the field of assistive technology, but also to the field of multi-sensory augmentation in human-computer interaction.

1. A User Study to Expand on Visually-Impaired User Experience with Technology and Pain Points

   This project integrates understanding the user's cognition, their social interactions, their interactions with technology and our understanding of building this technology using a systems approach to user-centered design. Moreover, this project further informs our understanding of how the visually-impaired interact with technology. This is very important as they make up a significant portion of the world's population and as we move into the fourth industrial revolution, it is imperative to know more about how we can build intuitive technology for this large subset of people.

2. Prototype 1 and Prototype 2 that work best for those with visually-impaired individuals with no light perception and work for other visually-impaired populations

   Both the iPhone-based prototype and the single-purpose wearable design prototype work to help identify and place potential interactors in the visually-impaired user's surroundings successfully. Prototype 2 is a more intuitive, easy-to-use, low-cost, low-energy solution to this problem. It has been shown to be most helpful for those with severe visual impairment with no light perception in both eyes. However, it is also helpful to other visually-impaired users with varying degrees of success. It helps them to a degree from which they can take over using their abilities. For example, it will tell a user who is visually-impaired in one-eye that someone is there in the visual field they cannot see in. In response to this, the user can turn such that they can perceive the potential interactor and space that was previously imperceivable to them.

3. Expanding the user-base to other age-related problems

   Having explored how potential users create mental maps of their surroundings, interact with the people in it and having built the technology to augment this information from multiple senses we can apply this solution to not only those with visual impairment, but also to those with other age-related problems such as dementia (memory loss), trouble recognizing faces (prosopagnosia) or even problems with depth perception.

1.5 Thesis Structure

Chapter 2 covers related work that has already been done in this area of assistive technology for the visually impaired, the technical and cognitive background required to design such systems and user interfaces, and an overview of user-centered design theory. The methods designed to evaluate the user experience and usability of the device are explained in Chapter 3. This is followed by a report of the results, a detailed discussion about them with key takeaways from each of these experiments in Chapters 4. Finally, Chapter 5 concludes the thesis with a discussion of limitations, challenges, key implications of this research and future directions.

2 Background

In this chapter, we cover the relevant basics of theory informing our understanding of the visually-impaired user's needs from how they build mental maps and create visual imagery to how they use their interpersonal space to engage in social interactions (social) as well as understanding existing assistive technology and user interface designs. Then, we delve into a short overview of the user-centered design process that we employ to design technology that best fits users' needs.

2.1 Related Work: Understanding Visually-Impaired Users' Needs

First, let us explore the social and cognitive background of our users and delve into the literature of assistive technology and multi-sensory interfaces. First, we will explore how the visually impaired create mental maps of their surroundings. Here, we delve into the potential differences between groups of visually impaired (such as those with early-onset blindness versus those with late-onset blindness). Then, we review the technical background and literature for building assistive systems and user interfaces for the visually-impaired

2.1.1 Understanding How Visually-Impaired Create Mental Maps

In order to augment the blind user's perception of those in their surroundings, we need to first understand how their mind perceives and processes the space around them. Most of the information required for this mental mapping is gathered through the visual channel. [39] Scientists have estimated that approximately one quarter of a sighted person's brain is devoted to visual perception. [21] People who are blind lack this information, and consequently they are required to use compensatory sensory channels and alternative exploration methods [30].

To examine the effects of nature and nurture on the human brain, we compare the minds and brains of sighted, congenitally blind and late-blind individuals. In sighted individuals, the occipital lobe, also called the visual cortex, responds to light detected in different shapes and orientations. However, in people who are blind the visual cortex responds to touch, sound and even language. [31, 35, 37, 50, 57, 69] In congenitally blind individuals (i.e. those born with blindness), the visual cortex responds more strongly to auditory and tactile stimuli than to visual stimuli. [52] This phenomenon is known as *cross-modal plasticity.* [7]

A key principle of cross-modal plasticity is *functional constancy.* [21, 49] This suggests that specialized brain regions, such as the visual cortex, continue to serve the same function but there is a shift in the region's primary sensory input. In our case, this shift is from sight to hearing or touch. Studies looking at cortical electro-physiology and functional brain imaging have shown that not only are the same brain regions activated, despite a change in the region's primary sensory input, there is little training required when working with technological interfaces that convey information via sounds and touch. [42, 60] Information about object recognition, movement or even changes in orientation could be successfully conveyed using auditory and tactile cues. Therefore, for the purpose of our study we can infer that auditory and tactile information is represented in the visual cortex of the blind the same way visual information is of the sighted.

Behavioral and brain imaging studies show that there is no significant difference between how individuals with early-onset blindness and late-onset blindness perceive their space. Both who lost vision earlier in life and those who lost it later in life, have been consistently reported to have activity in the visual cortex while performing non-visual tasks. However, people who lost vision earlier in life were more perceptive to changes in auditory cues while performing these tasks. [59, 61] This may be because they have had more time to adapt to the changes. Sometimes, individuals with late-onset blindness may also have hearing impairment alongside visual impairment. This is usually age-related. Since, age-related macular degeneration as well as other age-related diseases are a major cause for visual impairment it is important to understand the intersectionality of the individual's context.

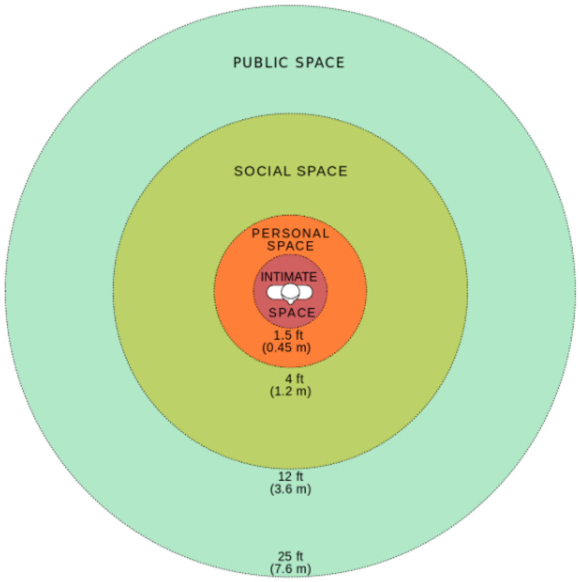
Furthermore, a blind individual learns at the same pace as a sighted individual. [59, 21, 60] Therefore, if we design systems and interfaces to be accessible to the blind there is no communication barrier and they learn as quickly as any other individual.

2.1.2 Understanding Use of Interpersonal Space

To design accessible and efficiently usable assistive technology that helps users engage in social interactions, we must study *proxemics*. Proxemics is the the study of human use of space and the effects that the people in our surroundings have on our behavior, communication, and social interaction. Edward T. Hall, the cultural anthropologist who coined the term in 1963, described the interpersonal distances between the interactor and others in the surrounding into four distinct zones: (1) intimate space, (2) personal space, (3) social space, and (4) public space. [26]

The distance surrounding a person forms their space. Intimate space is within about 1.5 feet of the person. It is used generally for confidential or really close interactions such as embracing, touching or whispering. Personal distance is within 1.5 to 4 feet of a person. This space is highly valued by the person as their space. Only close friends and family are welcome to enter their personal space. There is a distinction within personal space at about 2.5-4 feet where we sometimes interact with acquaintances, collaborators in group discussions, and other friends. However, most close interactions among acquaintances occur within about 4 to 7 feet, while other slightly casual interactions with acquaintances can happen from 7 to 12 feet. In very rare occasions, while making public speeches for example, we use the area between 12-25 feet of our relative distance to communicate with others. [26]

Figure 1: Interpersonal Space Model by Hall 1963 [v]



While we understand that this understanding of personal space and proxemics for interactions is highly variable based on cultural differences, we will be using this as a generic standard to base the design of our facilitation of interactions using the assistive device.

2.1.3 Understanding Intuitive User-Interface Design for The Visually-Impaired

Now that we have a background of how the visually-impaired build mental maps, and how we use the space around us to engage in social interactions, let us delve into how we can design the technology to build on top of these existing schema. First, we look to design an intuitive multi-sensory user interface. As we design the user interface, we are hoping that the auditory and haptic cues that we provide will intercept and follow the information processing route to the visual cortex where it will provide the user with a mental imagery of the location of the people in their surroundings.

Prior studies have used synthetic speech notifications - either text-to-speech audio or talking signs or replaying voice recordings to notify users. There are many devices that read graphics and text from screens out loud, read out the time, and even help in navigation and way-finding. However, our interactions with potential users show that these methods of constant notifications can be rather robotic, impersonal and frustrating for the user if they want to engage in social interactions while being notified constantly of changes in their environment.

Recent studies are exploring designing sonifications [11, 41, 60], haptic-feedback notifications [33] or a combination of both [8] for the cognitive mapping of unknown spaces for the blind.

For sonifications, most of the emphasis has been on designing the sonification itself by tuning frequency, timbre, and amplitude of the distinct sounds. Another strategy used by some studies is to build an environment from materials and objects that have distinct sound attributes that can be localized in space. Then, as the objects move in this space, we can construct a mental map of how far what objects are in our surroundings. Visually-impaired users were able to learn new sonifications and speech notifications in these studies with little to no training.

As for using haptic signals to map their surroundings, the cane used by many visually-impaired is an example of a low-resolution scanning of the immediate surroundings. Palms and fingers are also used for fine recognition of an object's form, texture and location, and feet for surface information. Some examples of tactile assistive technology include devices such as tactile braille displays, printers, tactile graphic displays and tactile mouse. We can modulate the pressure and frequency to create a haptic map of their surroundings to enhance existing cognitive maps. This has been fairly successful. [33] However, this mapping is very low-resolution, and it is hard to map on too many haptic cues as it becomes harder to learn and differentiate between different cues.

There are very few interfaces that are starting to look at 3D sound for notifications, but there are none that are currently looking at 3D sound for sonifications as well as haptic notifications. We pull from the designs in literature alongside our interactions with the potential users to understand how they perceive their world through sounds and touch to design a notification system that is intuitive, not cognitively overwhelming, and successfully directs the user's attention to augment their information about their surroundings.

2.1.4 Understanding Assistive Technology Design

Most of the work done so far in the technological research community to support the independence and social inclusion of the visually impaired has been done to enable smoother navigation. Assistive technology for the visually-impaired user to understand their surroundings has been extensively researched and created for both outdoor and indoor navigation by identifying objects, barriers and, entryways. [10, 14, 29, 32, 38, 40, 55, and many more]. Where outdoor systems rely upon GPS to locate the user [38, 40, 45] , indoor systems typically rely upon physical augmentation of the environment such as ultrasound [10,54, 58], Wi-Fi access points [20, 53] , radio frequency identifier (RFID) tags [14,44, 66] or expensive sensing equipment such as the systems based on computer vision [22, 55] or even integrated systems modeling the input from a combination of these [68]. There are also two recent research papers published that use Bluetooth Low Energy (BLE) beacons embedded in the environment and smart phone technology to help the blind with indoor navigation [3, 18]. A few studies also used Near Field Communication (NFC) or a system pulling from multiple sensors in real time to build a semantic-rich interior model of a building so that it is useful for navigation.

An example of such a navigation application is RSNAVI, built by Rosen Ivanov. [29] It is a context-aware indoor navigation system that uses information from RFID tags, and other sensors planted on the static surfaces of a building to build a semantic-rich interior model of the building and provides the user with step-by-step instructions on how to navigate the space in real-time. This is a very impressive system that does well to help the user navigate an indoor environment but does not provide any information about other people inside the environment that the user could engage with. It is also a very computationally expensive system that is bulky and unattractive to the user. It also is rather complex to use and the amount of information it provides could easily overwhelm a user. Therefore, this does not satisfy the user's need to engage in social interactions and it is not intuitive and easy-to-use by the user.

Another example of a low-cost low-energy mobile application is NavCog built by a team led by Dragan Ahmetovic at Carnegie Mellon University. This is a smartphone-based system that provides turn-by-turn navigation assistance based on accurate real-time localization over large spaces from Bluetooth Low-Energy beacons placed in the environment . It is useful in guiding visually-impaired users in unfamiliar and complex environments. [3] Other solutions also rely on pre-existing infrastructure such as Wi-Fi, Cellular signals, or GPS to manage their system architecture which can easily fail or not be available to the user at all times. Therefore, these solutions are not always reliable.

Most importantly, these solutions do not help answer our research question of identifying and placing *people* in the user's surroundings. These applications were designed for navigation around static objects such as walls, barriers, and objects. In our research problem not only is the user moving, but the potential interactors are also moving in the environment. While there is still work being done to improve accuracy, security and making these technologies more accessible at a low-cost to visually impaired users, these devices only detect stationary objects that are part of the environment, there is no significant research that has been done towards recognizing and placing other people (moving objects) in the visually-impaired user's environment. This gap in literature raises many interesting research questions in this field of assistive human-computer interaction. Our project hopes to answer some of these questions by designing assistive technology that helps people engage in social interactions.

2.1.5 Requirements for Product Design

Having understood how the visually-impaired build mental maps, how we use interpersonal space to engage in social interactions and the design of existing technology and user interfaces, we are now ready to design our own solution to help visually-impaired users identify and place people in their surroundings. In order to build a low-cost assistive device that reliably updates the user about their location and surroundings for every step that they take, we need to employ a technology that is low-cost, low-energy and updates accurately over each foot to map their social space. Furthermore, this should be largely independent of any pre-existing architecture or networks to ensure reliability even in case of errors or failures in the larger system. It should also be a fairly secure system.

Figure 2: Choosing Technology: Comparing Product Requirements v/s Different Technology Systems

Technology	**Product Requirements**				
	Low-cost	**Low-energy**	**Proximity mapping accuracy (within feet)**	**Identify individuals accurately**	**Independent of pre-existing architecture and networks such as Wi-Fi**
GPS	Green	Yellow	Red	Red	Yellow
Computer Vision	Red	Red	Green	Green	Red
Ultrasound	Green	Yellow	Green	Red	Green
Wi-Fi Access Points	Yellow	Green	Green	Red	Yellow
Infrared (Kinect-based sensors)	Yellow	Yellow	Green	Green	Yellow
Radio-Frequency Identification (RFID)	Yellow	Green	Green	Green	Green
Bluetooth Low Energy (BLE)	Green	Green	Green	Green	Green

Legend:

Green	Very Good (Ideal for our needs)	Yellow	Good (Fits our needs fairly well)	Red	Bad (Does not fit our needs at all)

- **GPS**

GPS technology is a satellite-based navigation system. It provides the geo-location to any GPS receiver on or near Earth where there is an unobstructed line of sight to four or more GPS satellites. It is great for mapping a route over a larger distance especially if it is outdoors. However, the signal is often blocked or weakened by buildings. Therefore, this technology is not so great for indoor positioning systems. Furthermore, it has an accuracy of about two meters therefore we cannot use this in this application because we need reliable information that updates for every step the user takes. GPS technology also does not serve our purpose of identifying individuals in our surroundings because it only helps with navigation. While many good assistive devices for outdoor navigation are based on GPS technology, we will not be employing it in ours.

- **Ultrasound**

Ultrasound is sound waves with frequencies higher than the upper audible limit of human hearing. Ultrasound is no different from 'normal' (audible) sound in its physical properties, except in that humans cannot hear it. This limit varies from person to person and is approximately 20 kilohertz (20,000 hertz) in healthy, young adults. Ultrasound devices operate with frequencies from 20 kHz up to several gigahertz. A common use of ultrasound is in underwater range finding; this use is also called Sonar. An ultrasonic pulse is generated in a particular direction. If there is an object in the path of this pulse, part or all of the pulse will be reflected back to the transmitter as an echo and can be detected through the receiver path. By measuring the difference in time between the pulse being transmitted and the echo being received, it is possible to determine the distance.

Many assistive devices detect objects and obstacles in their path using ultrasound technology similar to that of a sonar. It is fairly low-cost low-energy and can let you know if there are changes in the proximity to an object. It also does not need any pre-existing infrastructure. However, while ultrasound is a good way to determine if there is something in your path, it cannot recognize the object or let you know whether it is an object or someone you can interact with.

- **Infrared**

The Microsoft Kinect has an infrared depth sensor that is used by many applications to tell how far away things are. It many ways it works similar to the ultrasound technology. It has an in-built infrared projector that paints the scene in front of it with invisible markers (usually tiny dots). This allows it to triangulate the distance and angle between its two cameras and know which lines of sight belong to which object in space. A downside of this technology is that it works best indoors, as sunlight can wash out the pattern of invisible markers and multiple Kinects could confuse each other. This technology is fairly cost-effective and low-energy. However, it requires information to be processed using wireless networks in the studies that we have seen it applied. Its proximity mapping is fairly accurate within a couple of feet. However, it cannot accurately identify people.

- **Wi-Fi access points**

This technique compares the unique signal data from one or more external Wi-Fi (WLAN) access points sensed at a particular location with a map of prerecorded data. This technique requires a training phase in which the received signal strength at different locations are acquired and then stored in a database to create a map. In the next phase, when the user is navigating, the received signal strength or its distribution over time is measured and compared with the map to find the closest match. An advantage of WLANs signal localization is the relatively small number of base stations that are required for localizing the user. Owing to the increased prevalence of wireless networks in indoor environments, often no investment in infrastructure is required as existing base stations can be used. It is fairly low-cost and low-energy as well, however, it cannot identify others in the user's surroundings and therefore is not well-suited to our application.

- **Computer Vision**

There are a number of different computer vision systems that help visually-impaired users detect objects in their surroundings and find their way around an indoor or outdoor setting. Computer vision can be used to enable purposeful navigation and object identification. Purposeful navigation can be defined as guided motion through space toward a desired target while avoiding obstacles. The challenge is to robustly process the sensor feedback from a wearable system and to intuitively map the feedback to directions and semantic descriptions of the environment that meet the needs and goals of the user.

One such system is called Drishti. [55] Drishti is a very precise positioning system. It uses a wireless connection, a wearable computer, and a vocal communication interface to guide blind users and help them travel in familiar and unfamiliar environments independently and safely. While it is fairly efficient, it is very expensive, requires you to carry a cumbersome processing unit as a backpack as you navigate your everyday life. It depends upon pre-existing architecture of Wi-Fi therefore it is not reliable in case of no access to the Internet.

Recently, there have been studies that are designing real-time wearable system, which includes a camera, an embedded computer and a belt with embedded vibration motors that provides vibration feedback to signal obstacles to its users. This is reducing the restriction and cumbersomeness of previous devices. However, it is still not low-cost, low-energy, intuitive and does not help us recognize people in the users' surroundings efficiently.

- **RFID (Passive and Active tags)**

Radio-frequency identification (RFID) uses radio frequency to automatically identify and track tags attached to objects. The tags contain electronically-stored information that can be accessed by a receiver. There are two distinct types of RFID tags: Passive and Active. Passive RFID systems use tags with no internal power source and instead are powered by the electromagnetic energy transmitted from an RFID reader. Passive RFID tags are used for applications such as pet tracking, race timing, smart labels etc. These usually cost really low and can identify objects immediately.

On the other hand, Active RFID systems use battery-powered RFID tags that continuously broadcast their own signal. Active RFID tags are commonly used as "beacons" to accurately track the real-time location of assets or in high-speed environments. Active tags provide a much longer read range than passive tags, but they are also much more expensive.

Active RFID tags are much better suited to the needs of our project. It is a fairly low-energy way to identify objects and has pretty accurate ranging within a couple of feet. However, it is not low-cost.

- **Bluetooth Technology**

Our aim is to use Bluetooth Low Energy (BLE) beacons placed on the people in the environment as name tags that broadcast their identity, and location which can be picked up by the user's BLE signal receiver. Bluetooth beacons are in general low power consumption and low-cost transmitters which notify other devices of their presence much like a lighthouse does. These beacons employ the Bluetooth protocol to periodically send short signals to their surroundings. These signals contain the beacon identification data and can send also additional data like motion, temperature, or integrated data from other sensors. This will help the user not only identify the person, but also help them determine their proximity to this person and place them on their cognitive map of their surroundings.

Since a lot of elderly visually impaired individuals live in retirement communities or care facilities [1] , we will be designing this technology to work in this environment. Moreover, in our interactions with potential users who live in retirement housing communities, we found that the residents already wear name tags. Therefore, they are currently announcing their names to sighted people and we want to extend the same capability to people with impaired vision. Having a BLE beacon broadcast their identity to the user when they are in their interpersonal range will enable users to identify and independently interact with the name tag wearer.

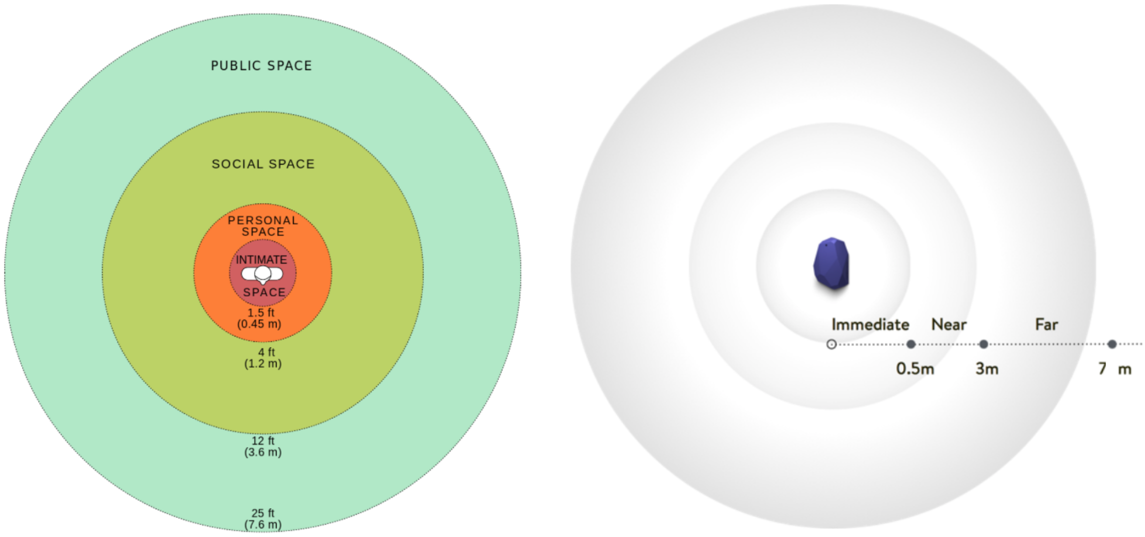
There is little difference between using Active RFID and Bluetooth Low Energy technology. However, the main difference seems to be that the BLE packets are distributed in such a way that it requires less energy. Also, Bluetooth receivers are cheaper than active RFID readers.

We chose to use Bluetooth Technology because it helps us map the immediate surroundings of the user within about 7 meters. These 7 meters covers the user's public space, social space, personal space and intimate space in which a user would interact with others. It provides context such as proximity while being a relatively low-cost solution. Furthermore, since these beacons are low energy, they do not need to be charged regularly. They last for about 1 year; therefore, they are durable and dependable. Additionally, these do not have to be oriented in a certain direction to be able to identify a person, they can identify and detect changes in ranges around 360 degrees of a user. Using BLE beacon technology is an intuitive, easy-to-use, low cost technology that is fairly secure and works well with the idea of interpersonal space for socializing, therefore is a great fit for our needs.

2.1.6 Understanding Bluetooth Low Energy Technology

In this project we will be using Bluetooth Low Energy (BLE) beacons as name-tags on potential interactors for our user. They will be broadcasting the identity and proximity of the potential interactor to the user who will have a Bluetooth receiver to decode this information. To work with this technology, we must first understand how it works from the hardware and firmware to the

Figure 3: The Proximity Zones of a Bluetooth Low Energy Beacon map onto the Interpersonal space zones in Proxemics theory fairly accurately[v, ix]



advertising packets and protocols.

Hardware and Firmware

The BLE beacon consists of a micro-controller with a BLE radio chip and a cell battery. In this project, we use Estimote Stickers Beacons which come with a Nordic Semiconductor's NF51822 chip-set and a 1,000 mAh cell battery. The beacons are completely enclosed and can be used in outdoor environments with some moisture, but this means the battery cannot be replaced - new beacons have to be purchased when the battery runs out. They have a flexible silicon covering them making their height about 3mm. The firmware on the beacon can be programmed to adjust the transmit power, the advertising interval and the beacon packet that it is broadcasting.

Beacon devices transmit a signal with a fixed base power, known as the Tx power. As the signal travels in air, the received signal strength decreases with distance from the beacon. Higher tx power means, the signal can travel longer distances. Lower Tx power means, less battery consumption but also smaller range.

The rate (frequency) at which a beacon emits a signal is its advertising interval. An interval of 100ms means the signal is emitted every 100 milliseconds (or 10 times in a single second). A higher interval of 500 ms means the signal is emitted only twice per second, which means less battery drain for the beacon. As the advertising interval increases, the battery life of the beacon also increases, but the responsiveness of the phone decreases. There is no optimal choice of advertising intervals, and applications needing low latency should choose lower advertising intervals, and those needing higher battery life should increase the advertising interval. Apple's official specification for the iBeacon protocol specifies an advertising interval of 100ms. However, most beacon vendors opt for a higher advertising interval while still adhering to all other aspects of the protocol.

Figure 4: Estimote Beacon Hardware[xi]

BLE advertising packets and protocols

BLE beacons broadcast a certain packet of information at a certain frequency and tx power. The information being broadcast contains a Universal Unique Identifier (UUID) along with other information packaged in one of 3 standard protocols: Apple's iBeacon protocol, Google's Eddystone protocol and Radius Network's AltBeacon protocol. All these three are types of GATT profile formats. The Generic Attributes (GATT) profile is a defined hierarchical data structure that helps us transfer data between a BLE beacon and a connected Bluetooth receiver device.

Apple's iBeacon protocol is a 30-byte packet that should be broadcast at 100ms intervals. iOS Apps which use the Core Location framework can ask the iOS to continuously monitor for beacon-region-crossing events, i.e., entering or exiting the proximity of an iBeacon defined by the UUID, Major and Minor fields. The iOS monitoring takes place whether the app is running or not and can even trigger a closed app to launch. Monitoring only works when the user has enabled Location Services for the corresponding app. We employ Apple's iBeacon protocol in the first prototype of our device.

Eddystone is an open-source, cross-platform beacon format from Google. It supports both Android and iOS devices. Unlike other beacon standards, it defines several different frame types which can be used individually or in combination: Eddystone-UID which broadcasts a unique beacon ID, Eddystone-URL which broadcasts Uniform Resource Locators (URLs), and Eddystone-TLM which can be used to broadcast telemetry (health and status) data about the beacon itself. The Eddystone-URL frame enables mobile platforms to offer web content based on proximity without requiring an app to be installed, enabling what Google has dubbed The Physical Web, or the "ability to walk up and use anything."

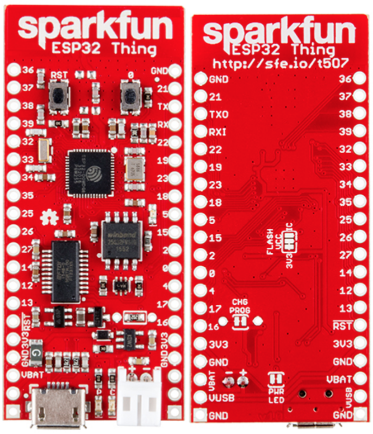
In this project, we only use the iBeacon and Eddystone URL protocols so we shall not be delving into understanding Radius Network's AltBeacon protocol. Overall, the AltBeacon protocol is an attempt to create an open-source standard that is independent of any manufacturer or their operating system.

2.1.7 Understanding Embedded Systems Used

To develop the second prototype which is a single-purpose wearable device we need to understand the basics of building an embedded systems solution.

Computing Power: ESP32 Board We need a board with a processing unit and memory to serve as a tiny computer on the user's wrist. We chose to use the ESP32 board, which is a low-cost, low-power system on a chip with Wi-Fi and dual-mode Bluetooth capabilities.

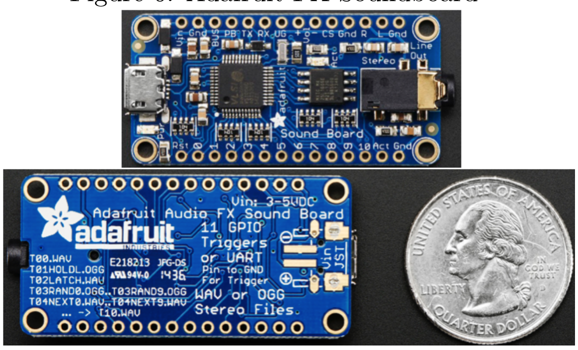
Figure 5: Sparkfun ESP-32 thing[i]



Sound

The Adafruit FX Soundboard is a simple, low cost audio effects trigger that is easy to use and does not require any programming. It can store up to 10 files on this board and play it as different cues. We soldered an audio jack to the soundboard so that the sounds can be transmitted to Bluetooth bone-conduction headphones. A Bluetooth transmitter that is plugged in to the audio jack. This transmits the audio cues via Bluetooth signals to a Bluetooth bone-conduction headphone.

Figure 6: Adafruit FX Soundboard[ii]



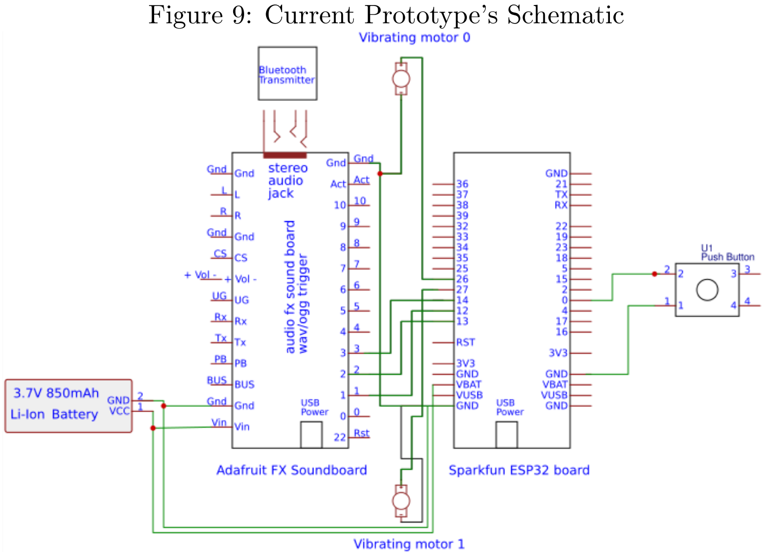
Haptic

We use 2 of Adafruit's Vibrating Mini Motor Discs to provide haptic feedback to the user. They are merely 10mm in diameter and weigh around 0.9grams. Then, we use a square tactile button

Figure 7: The audio and vibro-tactile user interface communicators. (Clockwise from top-left: Bluetooth transmitter, Bluetooth Bone-conduction headphone, Adafruit's vibrating mini-motor disk, and push button) [iii, iv]

Figure 8: Current Prototype: Single-purpose Wearable Assistive Device

Figure 9: Current Prototype's Schematic



switch around 6mm in size so that the user can easily find it and press it to get more information about the people in their surroundings.

Internet of things/Wearable Development Framework (IDF)

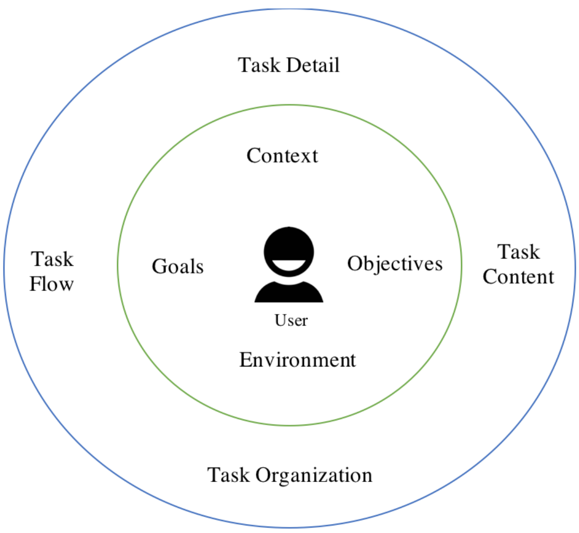
We use the Expressif ESP-IDF as a framework to develop applications for ESP32 chip by Espressif modified for use with the Sparkfun ESP32 Thing. The ESP-IDF, Espressif IoT Integrated Development Framework, provides toolchain, API, components and workflows to develop applications for ESP32 using Windows, Linux and Mac OS operating systems.

2.2 User-Centered Design Process

In the first section of this chapter, we understood the user experience based on literature and learnt the basics of how to build an assistive device. Now, we move on to learn more about how we can build an assistive device that caters each potential user's specific needs and wants. In this section, we will explore the user-centered design process that we employ to capture the user experience through understanding their needs and wants as well as feedback.

User-centered design, also called human-centered design, is a multi-disciplinary approach to interactive system development that focuses specifically on making systems usable. (ISO 13407, 1999) The key principle of user-centered design is gathering data from users throughout the process and then incorporating the findings into our product design. If we do this, users are more likely to like the product more and be more efficient using it. This approach lets us translate empathy-based concepts such as the real users' thoughts, feelings, frustrations and desires to systematic product specifications that we, as developers, can use to design our product such that it is easy for the user to learn and use.

Figure 10: The User-centered design model focuses on understanding tasks from the user's perspective



To gauge if this approach is used successfully, we measure the effectiveness, efficiency with which the user uses the product and their satisfaction using it in different contexts. The user-centered design model places the user at the center and aims to capture the whole user experience. We start the process by understanding the user, their goals, contexts, environment and objectives. What do they want to accomplish in a particular context or in a certain environment in the short-term and in the long-term? Why do they want to do something in a situation? Then, we understand the different tasks that the user will have to engage in and envision it as a journey that they take. We look at the details of the tasks themselves, its contents. Then, we explore how each task relates to the other tasks. How are the tasks organized and how do they flow from one to the other so as to accomplish different objectives towards the goal in this context and environment? By asking these questions we determine: who is the audience that will use this product? what is the purpose of this product? and, what is the context that will surround the use of this product?

User-centered design is an iterative process, where we focus on evaluating user needs and feedback from the very start through the finish aiming to build a highly usable and accessible system for each user. (Shawn Lawton Henry and Mary Martinson, Accessibility in User-Centered Design). We start the process by understanding the user and empathizing with their needs and wants in different contexts. We can understand user needs in a variety of ways: by creating personas, scenarios, or use cases, etc. However, in this study, we used the surveys and semi-structured interviews to evaluate user needs and wants in this particular project.

Once we have understood the user's needs in this context, we move on to define and structure the problem by clearly articulating it from the potential users' perspectives. Then, we brainstorm and generate creative ideas for potential solutions. This can be with the developer themselves or with some potential users. Then, we design a prototype to test whether our solution works intuitively or not. We ask potential users to test it out and provide feedback. In this study, we employ a think-aloud protocol which asks users to express without hesitation any thought or feeling that comes into their mind as they are using the prototype of the product. Then, based on this feedback we go back to repeat the either all or part of the previous stages to better understand user needs, refine the problem definition or design the product better to make it more usable, efficient and intuitive.

User-centered design is different than other design approaches as it tries to efficiently design the product to best match the users' needs, wants and feedback and integrating it as organically as possible into their pre-existing behavior patterns. The principles that ensure that a successful user-centered approach are the following:

1. The design is based upon an explicit understanding of users, tasks and environments.

2. Users are involved throughout design and development.

3. The design is driven and refined by user-centered evaluation.

4. The process is iterative.

5. The design addresses the whole user experience.
6. The design team includes multidisciplinary skills and perspectives.

3 Methods

In this project, we try to capture three different aspects: (1) user experience; (2) device's effectiveness; and (3) user's psychological and social behavior. In this chapter, we delve into the explanation of the methods used, why we chose to employ them, and how we measured and analyzed the data to inform the study and our design of the next prototype.

We employed the iterative user-centered design process to capture the user experience by understanding user needs and wants in different contexts and environments. Since we capture different types of data, we use a mixed methods approach. [16] First, we conduct semi-structured interviews surveying tasks the participants find challenging, assistive technology they use currently and have in the past and features they would like to see in a new device. Then, we assess their sociability and technological comfort to glean how we can best fit our design to their needs and behavior. We go back to the lab and develop the prototype - test it ourselves for technological reliability and usability. Afterwards, we come back to the users and test for usability. In usability testing we employ the think-aloud protocol and track task performance over different social tasks to gain insights on their thoughts and feelings as they perform these tasks both with and without the assistive device prototype. This process is repeated for each prototype version designed.

Mixed Methods Design

We employ a Mixed methods approach to collect and analyze qualitative and quantitative data. Quantitative data includes closed-ended information such as that found on attitude, behavior, or performance instruments. The analysis consists of statistically analyzing scores collected on instruments, checklists, or public documents to answer research questions or to test hypotheses. In contrast, qualitative data consists of open-ended information that the researcher gathers through interviews with participants. The general, open- ended questions asked during these interviews allow the participants to supply answers in their own words. Also, qualitative data may be collected by observing participants or sites of research, gathering documents from a private (e.g., diary) or public (e.g., minutes of meetings) source, or collecting audiovisual materials such as videotapes or artifacts. The analysis of the qualitative data (words or text or images) typically follows the path of aggregating the words or images into categories of information and presenting the diversity of ideas gathered during data collection. The open- versus closed-ended nature of the data differentiates between the two types better than the sources of the data. The sources of the data do not cleanly map onto qualitative and quantitative research. [16]

It is not enough to simply collect and analyze quantitative and qualitative data; they need to be "mixed" in some way so that together they form a more complete picture of the problem than they do when standing alone. There are three general ways in which we can mix the data: either merge the data so that they produce similar results, connect the qualitative to the quantitative to then infer the results, or embed the qualitative in the quantitative to explain the results.

In this study we will be collecting data in iterative phases. The first phase is a semi-structured interview with the potential users evaluating user needs and wants based on their life experience and experience with other technology. Then in the second phase, we ask them to fill out a survey containing psychological scales assessing sociability and technological comfort. The third phase tests the reliability of the prototype by the researcher. Finally, in the fourth phase we return to the user to collect feedback about usability and accessibility. The first, third and fourth phase might be iterated through for each version of the prototype.

Figure 11: Phases of Data Collection (Phases 1, 3 and 4 might be iterated through multiple times for each round of prototyping)

3.1 Capturing User-Needs: Semi-Structured Interviews

While a structured interview has an exact set of questions which does not allow one to divert, a semi-structured interview is open-ended in many ways, allowing new ideas to be brought up during the interview as a result of what the interviewee says. This list of questions and topics that have been thought about well-in-advance and need to be covered in a particular order during the interaction is called an interview guide.

Semi-structured interviews allow one to efficiently use time, be in full control of what you want from an interview but still allows you to pursue new leads from the participants. It is good to use this method when we may not get another chance to interview someone and want to get to know the range and depth of the participants' views on a certain topic. You can also reliably and easily compare different peoples answers to the same question to understand the differences in your participants. [9]

We want to develop a keen understanding of the participants needs and wants and empathize with their experiences as part of the user-centered design process. Furthermore, we have the limitation of only meeting our participants for a short period of time, possibly only once. Therefore, we chose to employ the semi-structured interview for Phase 1 of data collection.

Our interview guide is comprehensive spanning: (a) general information about extent of visual perception, duration of blindness and when they experienced vision loss; (b) usability feedback on assistive technology they have used before and are currently using (c) features that they would like to see in the implemented in the prototype. You can refer to the interview guide for the user needs evaluation phase in *Appendix A*.

We analyze the semi-structured interviews by aggregating the words into categories of insights collected and information used to inform different aspects of the design. We report these by quoting these words and phrases for results and then, presenting the assimilated insights from these diverse perspectives.

3.2 Usability Testing: Think-aloud Protocol and Task Performance

Usability testing refers to evaluating a product or service by testing it with representative users. Typically, during a test, participants will try to complete typical tasks while observers watch, listen and take notes. The goal is to identify any usability problems, collect qualitative and quantitative data and determine the participant's satisfaction with the product.

Think-Aloud Protocol

We employ the Think Aloud Protocol during usability testing to gain insight into the user's cognitive processes, comfort level and feelings while they are interacting with the device and performing various tasks. All interactions are audio- and/or video-recorded so that we can go back and refer to what users did, how they reacted, what they were comfortable with and what made them anxious.

Dr. Jakob Nielson, often referred to as the king of usability, in his 1993 book Usability Engineering defined the Think-aloud protocol as "asking participants to use the system while continuously thinking out loud - that is, simply verbalizing their thoughts as they move through the user interface". He deems this protocol to be "the single-most valuable usability engineering method". It is easy to implement this method and gain rapid, high-quality qualitative user feedback as compared with other methods (e.g. questionnaires). We can glean information about usability of the device by not only directly observing their use, but by also hearing what the subject wants and/or is trying to do. One of the down-sides of this method are that it is rather unnatural for us to voice out our stream of consciousness therefore we need to prompt the users. We can directly prompt the user for their insight by asking questions such as "what are you thinking now?", and "why did you do that?". We have to limit our prompts to not influence the user's experience and bias our study. However, these are easy to overcome. [47]

During usability testing we ask participants to perform a set of structured social tasks and think out loud to assess if the device affects sociability in real time. The social tasks ask the user to maintain a normal conversation with the researcher while either both of them are sitting, one is moving and the other is sitting, or both are moving towards or away from each other from different specified differences. Please refer to *Appendix B* for more details about the structured social tasks.

The participants are invited to a quiet room that facilitates thinking out loud. They are told to constantly think out loud and if they pause for more than a few seconds the experimenter prompts them to continue thinking out loud. The session is audio- and video-recorded as it is hard for the researcher to take note of all the verbal and non-verbal cues happening in quick procession. Once the think-aloud protocol session is complete, we interview the participant to capture their thoughts verbally by using a semi-structured interview.

There are two different ways in which we analyze the data collected. The think-aloud protocol allows us to gain insight into the user's perspective and provides us with qualitative data. The qualitative data collected from the Think-aloud protocol is not only verbal (words and phrases), but also non-verbal (gestures, body language, facial expressions, expressions of feelings such as sighs and groans, and even pauses or "uh"-s and "uhm"-s for hesitation or clarity). It is hard to capture, analyze and present all of the data in a written thesis. Therefore, we choose to capture and analyze only the verbal feedback. We try our best to report the pauses and other voiced expressions by transcribing them. We analyze and report this data in much the same manner as the data from the semi-structured interviews (i.e. by aggregating the words into categories of insights) while maintaining the order of the flow of thought. Since we will be briefly interviewing the users at the end, they will have another opportunity to assimilate their feedback and experience. By doing this, we ensure that we are able to capture their overall experience and feedback and do not lose any understanding that we might have gained by additionally capturing the non-verbal feedback in the moment.

Tracking Task Performance

Having captured the think-aloud data to inform us about usability, we also try to quantify the usability of the device by scoring the participants on their performance in each social interaction task. Usability for the purpose of this study is defined as the effectiveness and efficiency with which the user uses the device to independently perform tasks. This rubric is inspired from the Functional Independence Measure [36] usually used to evaluate the functional status of patients undergoing a rehabilitation following injury or operation.

First, the participants are asked to perform the structured social interaction tasks while using the device without any assistance from another individual. Based on their ability to successfully perform the task they are classified into main distinct categories of independence: No Helper, Helper - Modified Dependence and Helper - Complete dependence. In this situation, if the participant is only able to do less that 25% of the tasks, then they are classified as Total Assistance or Not Testable based within the Helper - Complete Dependence category. If the participant is able to complete 25% or more of the tasks, they are classified as Maximal Assistance within the Helper - Complete Dependence category. If the participant is able to complete 50% or more of the tasks, they are classified as Moderate Assistance within the Helper - Modified Dependence category. If the participant is able to complete 75% or more of the tasks, they are classified as Minimal Assistance within the Helper - Modified Dependence category. If the participant is able to complete 100%of the tasks in a timely and safe manner, they are classified within the No Helper category which means that they have complete independence. The participants can ask the person approaching who they are and still be classified into the no helper category as they have begun a social interaction on their own without any other individual's assistance.

Therefore, usability testing is successfully performed by employing think-aloud protocol to capture user feedback; and tracking task performance to capture changes in usability and efficiency of the developed prototype.

3.3 Behavioral Testing: Psychological Scales of Measure

There are a number of ways to measure psychological constructs such as cognitive and social ability in human factors research. One such way is to score each participant on a well-constructed, valid and reliable test called a scale or instrument. A useful psychological scale or instrument must be valid (meaning there is enough evidence to support the interpretation of the results as behavior) and reliable (meaning it is consistent in its results over time, different populations, different scorers, etc.).

In this study, we will be using standard psychological scales to measure the sociability, and technological comfort. Sociability is defined as the ability to be willing to talk and engage in activities with other people. In this study particularly, we define people who are sociable as those who are inclined to seek out the opportunity of social contact with others. We want to measure the inclination and want to engage in social interactions using the *Shyness and Sociability Scale for Adults*. This scale has 10 statements such as *"I feel inhibited when I am with other people"*, *"I easily approach others"*, or "*I really like to talk to other people"*. Participants are asked to rate each statement from 1 to 5 on a Likert-type scale based on how truly it describes them where *1 is "not at all"* and 5 *is "completely"*. Please refer to *Appendix C* for the sociability scale.

Technological comfort is measured by understanding if the individual is comfortable with and knows how to acquire new knowledge about technology. We chose to measure this because we wanted to measure the user's ability to not only use technology, but also to learn new technology because they will be learning to use a new device during this study. We use the 5-item *Acquisition of Technical Knowledge Scale* [5]. Participants rate each statement on a Likert-type scale of 1 - 5 based on how truly the statement describes them. *1= "not at all"* and *5= "completely"*. The statements are like: "*I spend time experimenting with programs I don't know very well in order to increase my knowledge"*, and "*If I have a problem using the computer, printer, fax, etc., I know where to seek help"*. Please refer to *Appendix D* for the Acquisition of Technical Knowledge scale.

4 Results and Result-Informed Design

Based on the technological literature review and our understanding of the social and cognitive background we designed our first prototype to help the user: (i) identify people they know in their surroundings and, (ii) place these people in distinct proximity zones of their mental map in relation to themselves. This was done to address the 3 original sub-problems: (i) not being able to recognize people in their surroundings, (ii) not knowing if the person they are interacting with is within hearing range, or still in the same room, and (iii) not being able to proactively greet people entering their social space.

Furthermore, having understood the idea of cross-modal plasticity, we wanted to design the user interface and notification system such that it would augment the existing neural processing pathways from the auditory and haptic stream to enable visual imagery. This was our understanding of initial user needs for this product. Therefore, the initial product requirements were that it should be:

1. Low-cost
2. Low-energy
3. Durable
4. Able to differentiate and map proximity zones fairly accurately (ranging within feet)
5. Able to identify individuals accurately and reliably
6. Independent of pre-existing architecture (e.g. Wi-Fi, Mobile signals, Satellite)
7. Intuitive i.e. integrates into existing behavior
8. Different notification streams: Speech Notifications, Haptic Notifications and Sonifications

4.1 Design 1: iPhone-based Design

4.1.1 Description and Implementation

The first prototype iOS application designed had 3 different versions and allowed visually-impaired users to identify people around them and inform them of their proximity to the other person through either designated (version 1) text-to-speech notifications, (version 2) sonifications or (version 3) vibrational haptic notifications. This application could detect when people in their surroundings were in motion or still, keep track of multiple people at the same time, and how close they are based on proximity zones (either immediate, near, far or unknown).

Now, let us delve into the details of how it worked. Each person that wanted to be detected by the user was given a BLE beacon that acted as a name tag that broadcasted at a particular

Figure 12: Prototype design 1: iPhone-based Design

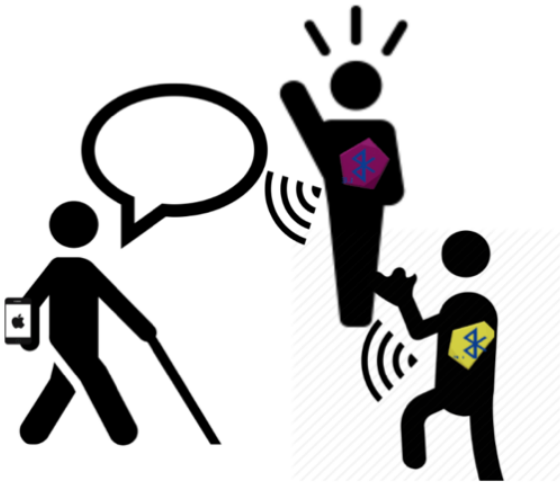
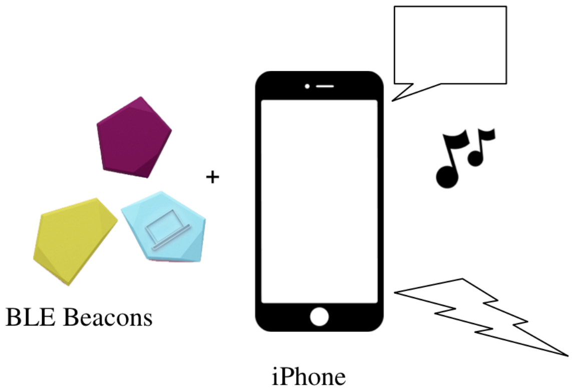


Figure 13: The iPhone-based Design notifies users using speech notifications, sonifications and vibrational haptic notifications



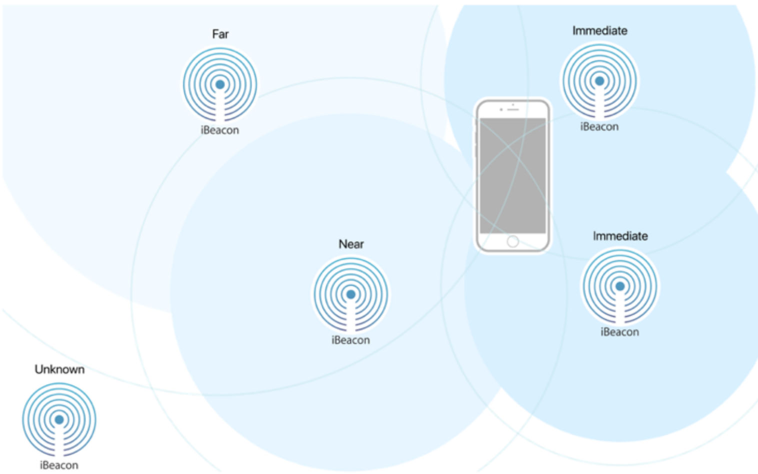
frequency the person's identity and whether they were moving or not. The beacon data includes exact UUID, major, and minor values of ranged beacons, as well as proximity estimations. The UUID is associated with the name of the person in the program written as a hash map.

Each beacon broadcasts its Bluetooth signal with a certain strength — a strength which diminishes as the signal travels through the air. This enables the receiver device to make a rough estimation of how far away the beacon is. The stronger the signal, the closer it is. In contrast, the weaker the signal the further away the person is. This signal was picked up by the Bluetooth receiver, which in this design was the iPhone.

The BLE beacons used were from Estimote, therefore we used their Estimote Proximity API [19] and Apple's Core Location API [4] that is part of the iBeacon protocol to design the iOS app. The ranging functionality in the Core Location API looks at the received signal strength indication (RSSI) and sorts the beacons based on the received signal strength, starting with the beacons closest to the user and going to those farthest away. This API also helped us categorize the RSSIs into 4 different categories or proximity zones: Immediate (strongest signal, usually up to 0.5m approximately), Near (medium-strong signal, up to 3m), Far (weak signal, up to about 7m), and Unknown (“hard to say”, usually when the signal is very weak and intermittent). These are just distance estimations. These are not accurate to the millimeter or centimeter but are good to estimate ranges in feet. This is not a concern for our use case because we do not need exact distances measured, we just want to determine approximate distances as proximity.

When the Bluetooth signal is received by the iPhone, it is immediately processed and conveyed to the user using the haptic or audio user interface depending on the app version. The first version of the app conveyed the information through speech notifications. These notifications were coded using Swift’s text-to-speech API using the class AVSpeechSynthesizer. The text to be spoken is instantiated as an AVSpeechUtterance. Then, the speak() function is used to “speak” that utterance. We manage the speech utterances to coincide with the events (e.g. movement into new proximity zone) using a AVSpeechSynthesizerDelegate protocol to manage the speech while the ranging of the beacons is managed by the iBeacon CLBeaconManager class. The second version of the app notified the user about changes in proximity zones using sonifications that employed the Apple’s AVAudioPlayer class. This class lets us store, play, pause, delay, and stop multiple audio files. The sounds are managed and synced with the event notifications using the AVAudioPlayerDelegate class. The third version of the app notified the user through haptic vibrational patterns. We designed different vibrational patterns using different instances of kSystemSoundID vibrate in different patterns with delays. We use the same event manager class that works with different delegate classes and protocols to play the vibrational pattern differently for different events occurring.

Figure 14: Ranging using Apple’s CoreLocation API and iBeacon protocol [vi]



There were some technical challenges that arose as we designed the iOS applications. Firstly, iBeacon ranging comes with certain trade-offs. First and foremost, ranging uses up more energy than just monitoring the beacons— although still less than GPS on the iPhone. Second, ranging works only when the app is active. As soon as the app transitions to a suspended state, ranging pauses until the app becomes active again. While we could not tackle first challenge of increased energy use because we want ranging to be active at all times for our app, we enabled beacon monitoring and ranging to be active in the background so that it would always be active to a certain degree. Finally, there was little consistency in different physical environments for the proximity zones. For example, while the "near" proximity zone was about 3 feet in my residence hall which had lots of walls and barriers, it was about 4-5 feet in the computer science department hallways. However, the variation was not significant enough. It can be explained by the number of obstacles the beacon signal has to pass through before being recognized by the iPhone. [28] This was actually kind of helpful in recognizing whether someone is in the same room (no barriers) or has left the room (increased number of barriers). As the beacon signal travels in much the same way as our voice, an audio signal travels through space and barriers, these inconsistencies sometimes mapped well on to how we used our voice to interact in these spaces. However, we would have to test the prototype in multiple environments to formally test this idea.

4.1.2 Usability Testing and User-Feedback

Once, we had designed the device, we ran a couple of tests to make sure it was reliable in its notifications and understand if it was cost-effective. The cost of the design was approximately $100 including about 10 beacons in addition to assuming that the user has an iPhone which is an average of $700. Therefore, this design is not the most cost-effective. However, it is better than some of the devices we discussed in our literature review. Furthermore, it was able to recognize the right person reliably all the time and report their proximity to the user immediately when tested.

Usability Testing Results

Then, we wanted to get some actual user feedback to understand whether this was actually an easy-to-use, intuitive design to recognize people in the user's environment and contexts. The participant (n=1) we interacted with was an 87-year-old female who had experienced late-onset blindness and was blind with no light perception

During the usability testing, the participant was sitting down while the researcher (playing the role of the potential interactor) was changing locations and proximity zones. The results are reported below in Figure 15 where *green* means the user completed the social interaction task successfully and independently (i.e. without assistance from anybody or thing other than the device itself), *yellow* means it was successful with some uncertainty and/or assistance from another individual and, *red* means the user was unsuccessful in maintaining a social conversation during the task or had to ask for additional assistance. *Grey* signifies that we did not test that case. The following table tracks the user's task performance and compares it to using the speech notifications, sonifications and haptic notifications versions of the app.

Figure 15: Usability Testing for Prototype 1: Tracking Independence in Task Performance

Sr. No.	User location and position	Potential Interactor's Location and Position	Independence in social interaction tasks (Sonifications version)	Independence in social interaction tasks (Haptic notifications version)	Independence in social interaction tasks (Speech notifications version)
1.	Constant position, sitting	Is standing within 3 feet distance of the participant (personal space)			
2.		Is standing within 10 feet distance of the participant (social space)			
3.		Is standing within 15 feet distance of the participant (public space)	N/A did not test	N/A	N/A
4.		Is moving between 3 feet and 10 feet distance from the participant			
5.		Is moving between 10 feet and 15 feet distance from the participant			
6.		Walks into the room and enters within 3 feet distance of the participant			
7.		Walks out of the room from standing before within 3 feet of the participant			

Legend:

	User completed task successfully and independently		User completed task successful with uncertainty and/or assistance		User was unsuccessful in completing social interaction task		Did not test

As the user interacts with the three different versions of the app, we notice some similarities. First, the user was able to successfully identify and place people in their surroundings in most of the tasks indicated by the green color in the independence in social interaction tasks column. Second, they only started talking when someone was in the "near" proximity zone. They did not really engage in a conversation when the potential interactor was in the "far" proximity zone. They merely acknowledged that they knew of their presence. However, when we discussed this with them, they suggested that this feature would only be useful if they entered a larger space such as an auditorium. In this case, they would like to know if someone they knew was already there so that they could go, sit near them and start a conversation. Third, the only time that there was some uncertainty during the task was when the researcher changed their position really quickly. When the researcher approached the user and when the researcher walked away from the user it was difficult to place them in their mental map of the space. This was because there was sometimes a lag between the potential interactor walking from one proximity zone to another and the interface notifying the user. This might be because the potential interactor changed proximity zones faster than the frequency of the beacon broadcasting its signal. For example, as a person was approaching the user it reported that they were far and then immediately after that they were in their immediate surroundings. While, this can be rather confusing, the user did not bring this up as a major issue. This could also be because it takes more time for the speech notification to say “Person A is near” than for a sonification or a haptic notification to just ping the user. Overall, all three versions of the app were successful in helping the user locate and place people in their surroundings.

On the other hand, there were some differences in how the user interacted with the different versions. The user performed similarly while using both the haptic notification and sonification user interface versions. They were able to use the device and maintain a conversation. However, their performance was drastically different while interacting with the speech notifications version. In the speech notifications user interface, while the user could identify who was in their surroundings, they could not maintain a conversation. This might be because they kept getting interrupted by the speech notifications. They were distracted by it and mainly just listened to it repetitively notify them. After a certain point in time, the user grew weary of the speech notifications and then slowly frustrated. The same was true of the sonification user interface, just to a lesser degree. They were happy with the vibro-tactile haptic interface version. Furthermore, they could not distinguish well between when someone enters or leaves the room.

Overall Feedback from Think-aloud protocol results

The user liked that there were vibration patterns as well as sonifications which would be suited to different contexts and environments in their daily routine. They did not like the voice as much. They mentioned it was really useful “to recognize [someone] from a distance.” You can say “Oh I see [Person A]! I should go to him. The name is always useful.”

On the other hand, they did not like the constant notification system. They said, “It is useless and irritating when she [the notification system] keeps talking all the time.” They expressed signs of displeasure and discontent on the repeated speech notifications. Furthermore, they talked about how there was only a need to be notified when someone is arriving, leaving or if there is a change in position. For example, “[Person B] is arriving” and “leaving” rather than a constant stream of “[Person A] is near.” They also mentioned that they would like to access different notification patterns based on different environments that they are in. For example, a more significant notification for when they are in the hallway versus a less noticeable notification system for when they are in a much more social space with a lot of activity going on that they need to attend to (such as a dining hall or café). Additionally, if there was a call or message on the iPhone there was already a lot of attention and cognitive resources given to attending to the call or message. As the app runs in the background, it would continue notifying therefore, overwhelming and frustrating the user further. The challenges faced, and improvements suggested indicated that the current notification system with constant speech, audio and haptic notification was too cognitively overwhelming and frustrating for the user.

In conclusion, while the user was able to successfully detect where the potential interactor was and changed their voice and interaction pattern accordingly they were cognitively overwhelmed by the constant notification system. Therefore, 2 goals of the design were met – to recognize people and place them in a mental space. However, our goal of making the device easy-to-use and intuitive was definitely not met in this design prototype.

Understanding devices used every day – Semi-structured interview results

Since the device's user interface was unintuitive and cognitively overwhelming for the user, we inform our design by looking to the devices that they use successfully and rely on every day. To expand our understanding of their user experience, we interviewed the user about devices they successfully used routinely. The results from that conversation are that they successfully currently use technologies such as the VictorReader by HumanWare, Color Teller, Clock, Wristwatch, Cane. On the other hand, they less successfully use iPhone features such as Siri, VoiceOver, ScreenCurtain, and the double-tap gesture to pick up calls. They have also successfully used canes and flip-phones successfully in the past.

Figure 16: Devices used every day: (Left-to-righ) VictorReader by HumanWare, Color Teller, Flip phone, Alarm Clock (top), Wristwatch (bottom) [vii, viii,x]

VictorReader by HumanWare is a handheld media player that reads out books to the visually-impaired user. The participant has used it for "many years" and only took about "1 month to get familiarized". They like that the voices in the player are personable. While there are many features to this device such as being able to "pause it, bookmark, take notes, etc. - but haven't used these features"

Next, we looked at the Color Teller. "It is a talking color identifier that helps those who are blind or have a color vision impairment to determine the color of materials or objects. Announces all the common colors, plus many tints and shades like pink, pale blue-green, dark brown and vivid yellow. It is about 6 inches long, about 3 ounces and is very durable." When asked about the time taken to get familiarized with the device, the participant replied, "not long at all" and have been using the device for quite a while. "It's reliable and very useful as I pick out my outfits every morning."

The clock and the wristwatch were also used every day for a long time making it a part of her routine as she described how she used these devices: "Before going to bed you set the alarm and it wakes you up at the correct time and beeps. It is reliable" and "I wear it every morning and press the button to tell the accurate time." These devices seemed to be pretty intuitive to use and learn because they mentioned that they were immediately able to use it and were familiar with its use.

Regarding the iPhone she said that she was, "Still not familiarized at all. [I] attended classes and was very good at it at the time. However, it's been really difficult since. Would like to reconnect with her fellow classmates and hopes it will help her keep up with it." "The voice-over voice and its timing are very frustrating. To a person who cannot see the display, it is useless and irritating when she keeps talking all the time. Even in the middle of a call." "[It] drives me crazy!" Particularly about the double-tap feature and *Siri* she said, "It's very unreliable and frustrating."

In contrast, talking enthusiastically about their use of a flip phone she said, "I mainly used to place calls and receive them." "It's reliable. It has a single use. It has raised bumps on its numbers - 1, 3, 5, 7. And a button to turn it off and on." When asked about the reason for their switch to the iPhone, she said that she, "Wanted to be more modern and thought that the added functionality in the iPhone should be easy to learn."

She also mentioned having used a cane briefly in the past. She said it, "is reliable. It has a single use." However, when asked why she does not use it anymore, she said "Not much use for it since I have someone with me at all time who helps guide me. But if I became more independent, I might possibly use it to independently explore new places."

Reviewing the devices used successfully, we gleaned that no matter the primary function of the device they were largely single-purpose devices. When asked about this, the potential user agreed and said that it was much more reliable to use a device that she knew would work for its assigned purpose. There is no confusion in how to use it and what its output will be. It is "easier to learn" single-purpose devices.

4.1.3 Insights gained

From this interaction we mainly learnt 3 things: (i) Single-purpose devices, like the Color Teller, are easier-to-use and intuitive for our visually-impaired potential user (ii) Even if there is more than a single purpose to the device, these features and use cases are likely not going to be used, as shown by the Victor Reader or Flip-phone, and (iii) Users are truly open to ideas and technologies to make them more independent. While we were encouraged by particularly the third insight, we also realized that we had to completely revamp our design and move away from the cognitively overwhelming iPhone-based design to design and develop a more single-purpose device.

We went back to the drawing board and updated the product requirements to accommodate our expanded understanding of the user experience:

1. Single-purpose device
2. Low-cost

3. Low-energy
4. Durable
5. Able to differentiate and map proximity zones fairly accurately (ranging within feet)
6. Able to identify individuals accurately and reliably
7. Independent of pre-existing architecture (e.g. Wi-Fi, Mobile signals, Satellite)
8. Intuitive i.e. integrates into existing behavior
9. 3 Different notification streams: Speech Notifications, Haptic Notifications and Sonifications that updates the user only when people have significantly changed their location in the user's surroundings.

4.2 Design 2: Single-purpose Wearable Design

Our goal with this design prototype is to design a single-purpose wearable device that will be able to provide not only sonifications, but also haptic notifications such that the visually-impaired user is able to identify and place people in their surroundings.

4.2.1 Description and Implementation

In order to make this a single-purpose device we need to move away from the iPhone-based system design to an embedded systems design. Furthermore, since the Bluetooth receiver would need to be on them at all times, we designed it to be a wearable. This wearable will be a wrist-based wearable because the participants already have a routine of wearing a wristwatch as they get ready for the day. Having a wrist wearable integrates well into this routine. Furthermore, this wrist bracelet will not only hold the Bluetooth receiver and processing, memory aspects of the device, but also serve as the vibro-tactile interface. This wearable has a counterpart Bluetooth bone conduction headphone which serves as the audio interface providing both speech notifications and sonifications. We choose to use a Bone-conduction headphone so that we can augment the incoming audio cues that they are already using to build their mental map without blocking it. The bone-conduction headphone also ensures a level of privacy since the sound is only transmitted by vibrations, only the wearer hears the notifications.

Hardware + User Interface Implementation

Now, let us delve into how this device actually works. The BLE beacons send out a signal with the identity of the person wearing it. This is received by the Bluetooth receiver in the bracelet at a certain Received Signal Strength Indication (RSSI). The program recognizes people based on hash map that has UUID-person pairs. The beacons (i.e. people) in the surroundings are sorted

Figure 17: Design Prototype 2: Single-Purpose Wearable Assistive Device with a audio-haptic user interface

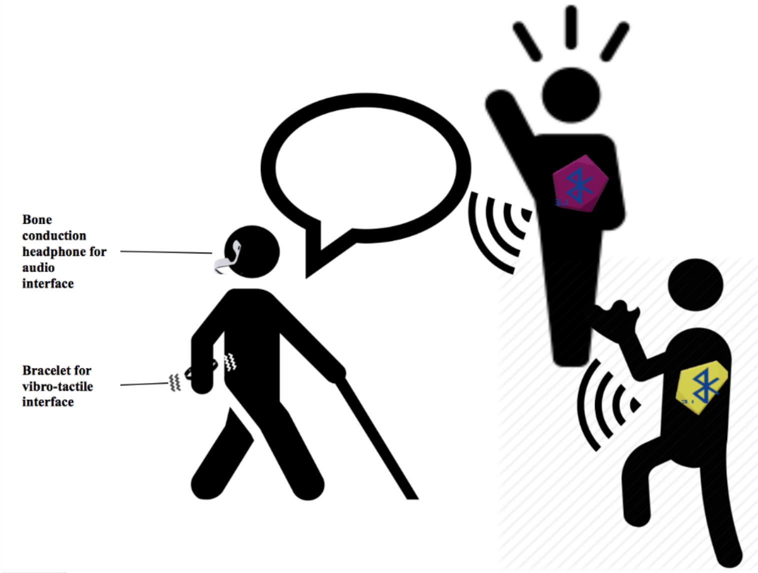


Figure 18: Single-Purpose Wearable Assistive Device Prototype

by our program into 4 different proximity zones based on the received signal strength received. The lower the RSSI, the farther away the beacon/person is. The stronger the RSSI, the closer the beacon/person is to the Bluetooth receiver on the user's wrist. The four different proximity zones are the same as the previous design: Immediate (really strong signal, really close and within the personal space, about 0.5m), Near (moderately strong signal, close and within social space, about 3m), Far (weak signal and within public space, about 7m), Unknown (really weak and intermittent signal, don't know where the person is)

Figure 19: Single-Purpose Wearable Assistive Device Prototype: Inside the case

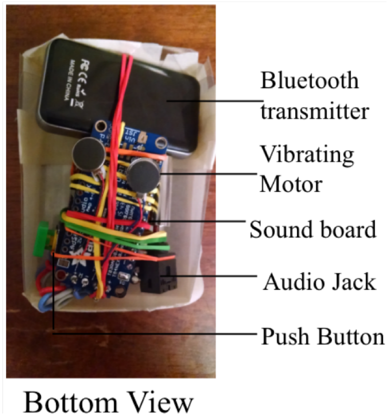
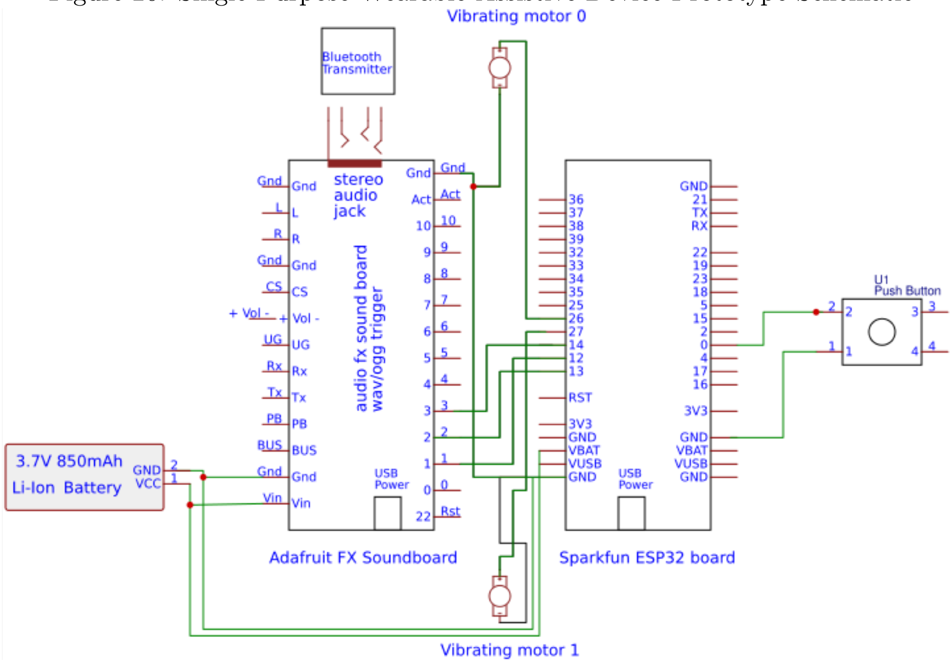


Figure 20: Single-Purpose Wearable Assistive Device Prototype Schematic



The Bluetooth receiver is built into the Bluetooth module of the ESP32 chip that we use to store and process the data being received and sent out. It is a really small board that would fit well on someone's wrist. The ESP32 chip has a Bluetooth Low Energy-compatible micro-controller, 30 input/output pins, and an FTDI FT231x, which converts USB to serial, and allows us to program the micro-controller from our computer. We power the ESP32 board using a Lithium-polymer battery to make it portable. There is also a mini-USB charging port which we used during most of the testing prototypes.

To enable sonifications and speech notifications, we use the Adafruit FX Soundboard because it is really small (about 1.9" x 0.85") and portable. It can store about 2MB worth of sound and can be powered by a 3-5V Lithium-Polymer battery. It has about 11 triggers, therefore we can notify the user of about 11 different events with different sounds. Since each user has about 4 tunes (2 speech notification sounds, 2 sonifications) that are dedicated the device can convey information of about 3-4 people without cognitively overwhelming the user with too many different sounds. It is easier to learn to differentiate between and keep track of about 10-11 sounds. [31, 57, 59] Therefore, this is perfect for our use case. Each of the distinct sounds stored in the Soundboard are triggered in response to events occurring in the user's environment as they are informed by signals from the ESP32 I/O pins.

The sounds differ in amplitude and vibration as a person changes their location in the 3 proximity zones. Ideally, one should be able to assign a type of sound to a person much like assigning a ring tone for a person in your mobile phone. The sounds become louder and higher in pitch when the person is closer to you. Therefore, it is the loudest and has the highest pitch when a person is in immediate proximity, however it becomes fainter as the person moves from the immediate to near and then far proximity zones.

The Adafruit Soundboard is connected to a 3.5mm Audio Headphone Jack. Since we want the sonifications to be conveyed via the Bluetooth bone-conduction headphones we plug in a Bluetooth transmitter to this audio headphone jack. This way the sounds are transmitted to the headphone which then play the sounds and transmit it directly to the user's inner ear. The bone conduction headphone is placed on the user's cheek bones. The sound vibrations are conducted into the user's inner ear through the bones of the skull. We choose to use the bone-conduction headphone as the audio user interface because we did not want to block any sounds that the user is already using to build their mental map, but just wanted to add to the cues that they are already using.

The vibro-tactile interface is controlled by two motors connected to the ESP32 chip. The motors vibrate at 3 different frequencies depending on the proximity zone that they are in. The higher the frequency of vibration, the closer the person is. Therefore, the motors vibrate really vigorously when the person is in the immediate zone and become fainter as a person walks to the near and far proximity zones.

The total cost of making this device is about \$200. This total cost can be broken down into the bill of materials as: \$20 for the Adafruit Sound Board, \$20 for the ESP32, \$5 including the audio jack, motors and the casing, and about \$50 for the Bluetooth bone-conduction headset along with \$50 for 3-4 Bluetooth Low Energy beacons and \$20 for the Lithium-Polymer battery.

Software Program Implementation

Having discussed the hardware and the interface, now let us discuss how the software was developed. We coded a completely new program that is completely independent of the one developed for the iphone-based design. The only similarity is in the concepts and ideas used.

Since we were programming the ESP32 board directly, we used the Espressif Internet of Things (IoT) Development Framework (IDF) from the command line by connecting to the board using USB to establish a serial connection with the board. The program was coded in C++. This is a complete shift from using XCode and Swift to program the first prototype.

We also changed the BLE protocol we use from iBeacon to Eddystone URL. We shifted this because we were now free from the iOS platform and wanted to make our single-purpose wearable compatible with any device. Eddystone URL packets can be received and processed by not only an Android or Google device, but any Bluetooth receiver.

Since we are not using the iBeacon protocol, Apple's CoreLocation API nor the Estimote Nearable API, we must develop our own algorithm for ranging the beacons and classifying them into the different proximity zones. When BLE beacons' Eddystone URL packet/signal is received by the ESP32 board (i.e. a person is detected nearby), the program notes the unique identity (UUID) of the beacon and begins ranging.

First, to determine proximity zone based on the Received Signal Strength Indication, the program sorts the beacons from the closest (strongest RSSI) to the farthest (weakest RSSI) and classifies each beacon into a proximity zone (either immediate, near, far, or unknown). Second, to identify the person the program looks up the URL-Name pair from the hashtable. Then, the program reports the identity and proximity of the potential interactor to the user through the audio-haptic user interface.

The timings of the scans are set to coincide with the frequency at which the beacon is transmitting. Our program is currently set to scan about every 4 seconds which is when the beacons are also set to broadcast. Additionally, the program is built to handle possible errors and scan failures

Once the program categorizes the identity and the proximity of a beacon, it sets the pins that correspond to the particular sounds on the sound board and vibrational patterns of the motors to turn on and produce the respective sounds and vibrational patterns. This all happens almost in real-time. Therefore, the user is notified almost as the signal is received from the beacon. While the sonifications and the haptic notifications are reported to the user in real-time, the speech notifications are only reported when the user wants to know exactly who is in their surroundings. There is a push button that the user can press to ask the device who is in their surroundings. Then, the device will accordingly produce the speech notification with the name of the person. This is to prevent overwhelming the user with a constant stream of speech notifications.

Furthermore, since the biggest issue with our previous design was the constant stream of notifications which frustrated and overwhelmed the user we did not want to continue that in this design. This user interface only notifies the user when there is a change from the previous state. The program scanned the surroundings every 4 seconds however, it stores the information every 3 scans and only reports if there is a change in the beacon information past 3 scans. A difference in the proximity zone in 3 scans indicates that the person has moved in the space. If there is not a difference in the last 3 scans it means the person is in the same proximity in the user's surroundings and the user does not need to be notified.

Technical Design Challenges

During the process of designing and developing this system, there were quite a few technical challenges and number of insights gained as result of these challenges, . Since, we could not directly transfer our code from the first design to the second, there were new things to be learnt in this phase of design. In the first design, we had to develop just the program. In the second design, we had to develop both the hardware and the software. We did not have a well-developed, and supportive development framework like we had for iOS development. The ESP32 board with Bluetooth capability and the Espressif IoT development framework that we used heavily in this project had just recently been released for the very first time. Due to the lack of documentation and community working on this, there was a steep learning curve for all of us. On the bright side, it was really exciting to be one of the few people working on this new and exciting technology and discover things first-hand alongside the online open-source community. This was especially fascinating since I had never engineered an embedded systems project before but was learning about this technology rapidly to apply it to a goal which I was passionate about.

Usability Testing and User Feedback Process

Having discussed the design and development of this device, let us now delve into testing this device. We conducted multiple iterations of usability testing and collecting user feedback. Initially, I tested the device on myself by blindfolding myself and wearing the device to "pseudo-simulate" the user experience of a potential visually-impaired user. During this iteration, we tested performance and usability in a large, noisy dining hall setting, and a small quiet residence hall room setting. For the next iteration of usability testing and user feedback collection, we interacted in a quiet classroom setting with a 20-year-old female who had no light perception since birth. For the final iteration, we engaged with 5 participants in a local retirement community and assisted care living facility. In this sub-section, we will delve into our results, and insights gained during each of these iterations.

4.2.2 Initial Usability Testing Results

In order to initially test this device to understand the usability, and intuitiveness, I blindfolded myself to simulate the user experience and wore the device. I tried to perform the structured social interaction tasks without any assistance but that of the device. One of my friends played the role of the potential interactor. This testing was done in two environments: a noisy large dining hall, and a quiet small residence hall room. The results are reported below in Figure 21 for a large dining hall, and in Figure 22 for a small quiet residence hall room). In these figures: green means the user (here, me) completed the social interaction task successfully and independently (i.e. without any assistance other than the device itself), yellow means it was successful with some uncertainty and/or assistance and, red means the user was unsuccessful in maintaining a social conversation during the task or had to ask for additional assistance.

Figure 21: Usability Testing Prototype 2: Tracking Independence in Task Performance in a noisy large dining hall

User location and position	Potential Interactor's Location and Position	Independence in social interaction tasks
Constant position, sitting	Is standing within 3 feet distance of the participant (personal space)	
	Is standing within 10 feet distance of the participant (social space)	
	Is standing within 15 feet distance of the participant (public space)	
	Is moving between 3 feet and 10 feet distance from the participant	
	Is moving between 10 feet and 15 feet distance from the participant	Inconsistent reporting of distances – both reported as "far"
	Walks into the room and enters within 3 feet distance of the participant	Hard to distinguish when they are in the same room. Only interacted with person when person is reported to be "near" them
	Walks out of the room from standing before within 3 feet of the participant	Continues reporting as "far" even if person is outside the room – Therefore hard to tell when they are outside the room
Is moving between 3 feet and 10 feet distance from the researcher	Constant position, sitting	
Is moving between 10 feet and 15 feet distance from the researcher		Inconsistency in reporting – Reported as "far" or "lost" or sometimes even near
Walks into the room and enters within 3 feet distance of the researcher		
Walks out of the room from standing before within 3 feet of the researcher		
The participant and the researcher are both moving such that they are approaching each other from being initially 10 feet apart		
The participant and the researcher are both moving such that they are moving away from each other after being initially 3 feet apart		
The participant and the researcher are both moving such that the participant enters the room that the researcher is moving around		
The participant and the researcher are both moving such that the participant exits a room in which the researcher is moving around		
The participant and the researcher are both moving such that the researcher enters into the room that the participant is moving around		
The participant and the researcher are both moving such that the researcher exits a room in which the participant is moving around		

Legend:

	User completed task successfully and independently		User completed task successful with uncertainty and/or assistance		User was unsuccessful in completing social interaction task		Did not test

The way in which I interacted with the device and my surroundings in the two different environments had some similarities. Overall, in the role of the user, I was able to successfully identify who was in my surrounding and how far away they were. It was not cognitively overwhelming as the device only notified me when there was a significant change in the potential interactor's location as shown by a significant change in RSSI over a period of 3 signals. Furthermore, I was

Figure 22: Usability Testing Prototype 2: Tracking Independence in Task Performance in a quiet small residence hall room

User location and position	**Researcher Location and Position**	**Independence in social interaction tasks**
Constant position, sitting	Is standing within 3 feet distance of the participant (personal space)	
	Is standing within 10 feet distance of the participant (social space)	
	Is standing within 15 feet distance of the participant (public space)	
	Is moving between 3 feet and 10 feet distance from the participant	
	Is moving between 10 feet and 15 feet distance from the participant	"Far" or "lost" – sometimes it is inconsistent
	Walks into the room and enters within 3 feet distance of the participant	
	Walks out of the room from standing before within 3 feet of the participant	The room entrance is about 3-5 feet away. Therefore, *sometimes* might report as still being near.
Is moving between 3 feet and 10 feet distance from the researcher	Constant position, sitting	Sometimes reported as near, and sometimes as far proximity zone
Is moving between 10 feet and 15 feet distance from the researcher		
Walks into the room and enters within 3 feet distance of the researcher		
Walks out of the room from standing before within 3 feet of the researcher		
The participant and the researcher are both moving such that they are approaching each other from being initially 10 feet apart		
The participant and the researcher are both moving such that they are moving away from each other after being initially 3 feet apart		
The participant and the researcher are both moving such that the participant enters the room that the researcher is moving around		
The participant and the researcher are both moving such that the participant exits a room in which the researcher is moving around		
The participant and the researcher are both moving such that the researcher enters into the room that the participant is moving around		
The participant and the researcher are both moving such that the researcher exits a room in which the participant is moving around		

Legend:

	User completed task successfully and independently		User completed task successful with uncertainty and/or assistance		User was unsuccessful in completing social interaction task		Did not test

okay with just having different beeps differentiated by differences in amplitude and frequency to signify differences in proximity zones. However, we need actual user feedback to better help design comfortable, and non-obtrusive sonifications. Here, I also need to identify my own biases in this process since, I was the developer of the technology as well as the software, I knew what was going to be reported. Also, I was only focusing my attention on these social interaction tasks and not engaged in other things during the testing.

There were a few uncertainties and issues during the tasks. First, there were blurred lines between what is considered as a proximity zone boundary. One instance when this happened occured when someone moved quickly through space. Other instances that it occurs in were dependent on the broadcasting and reporting frequency as well as characteristics of the physical environment itself (such as the obstacles in the signal path). For example, it classified and reported the proximity zones at different distances in my residence hall room, with many walls and obstacles, compared to that in the open dining hall. For example, it reported "far" as "near" sometimes, because of measuring RSSIs which are not the most accurate measure of distance. However, in our use case we do not want it to be absolutely accurate. Also, it was easier to differentiate the changes in the proximity zones if I was in the quieter setting of my residence hall room compared to the loud dining hall. Second, I did not feel comfortable interacting with people who were far. I mostly only started a conversation when someone was announced to be "near" me. This might have been a personal characteristic need that needs to be verified with other users' experiences. Third, at this point the wearable was rather huge and bulky because it was rooted in a breadboard and used a portable battery charger to power it.

Overall, my personal feedback while blindfolded showed that not only was the user able to correctly identify and place people in their mental maps, the user was also not getting cognitively overwhelmed by the interaction with the device. Having tested this new single-purpose prototype myself, we decided to collect user feedback from an actual potential user of this device.

Insights gained

This new single-purpose wearable device is more intuitive and easy-to-use than the previous device and can still identify and place people fairly accurately. However, there is a need to calibrate the proximity zones for different proximity zones in different physical environments.

4.2.3 Usability Testing – User-Feedback Round 1

We first collected user feedback from a 20-year-old legally blind female with no light perception who experienced early-onset blindness. The social interaction tasks took place in an empty classroom over a period of an hour. She had a guide dog to help her navigate the space. Her usability testing results are reported in Figure 23.

Figure 23: Usability Testing Prototype 2: Tracking Independence in Task Performance in a classroom by a potential user

<table>
<tr><th>User location and position</th><th>Researcher Location and Position</th><th>Independence in social interaction tasks</th></tr>
<tr><td rowspan="7">Constant position, sitting</td><td>Is standing within 3 feet distance of the participant (personal space)</td><td></td></tr>
<tr><td>Is standing within 10 feet distance of the participant (social space)</td><td></td></tr>
<tr><td>Is standing within 15 feet distance of the participant (public space)</td><td></td></tr>
<tr><td>Is moving between 3 feet and 10 feet distance from the participant</td><td></td></tr>
<tr><td>Is moving between 10 feet and 15 feet distance from the participant</td><td></td></tr>
<tr><td>Walks into the room and enters within 3 feet distance of the participant</td><td></td></tr>
<tr><td>Walks out of the room from standing before within 3 feet of the participant</td><td></td></tr>
<tr><td>Is moving between 3 feet and 10 feet distance from the researcher</td><td rowspan="4">Constant position, sitting</td><td></td></tr>
<tr><td>Is moving between 10 feet and 15 feet distance from the researcher</td><td></td></tr>
<tr><td>Walks into the room and enters within 3 feet distance of the researcher</td><td></td></tr>
<tr><td>Walks out of the room from standing before within 3 feet of the researcher</td><td></td></tr>
<tr><td colspan="2">The participant and the researcher are both moving such that they are approaching each other from being initially 10 feet apart</td><td></td></tr>
<tr><td colspan="2">The participant and the researcher are both moving such that they are moving away from each other after being initially 3 feet apart</td><td></td></tr>
<tr><td colspan="2">The participant and the researcher are both moving such that the participant enters the room that the researcher is moving around</td><td></td></tr>
<tr><td colspan="2">The participant and the researcher are both moving such that the participant exits a room in which the researcher is moving around</td><td></td></tr>
<tr><td colspan="2">The participant and the researcher are both moving such that the researcher enters into the room that the participant is moving around</td><td></td></tr>
<tr><td colspan="2">The participant and the researcher are both moving such that the researcher exits a room in which the participant is moving around</td><td></td></tr>
</table>

Legend:

	User completed task successfully and independently		User completed task successful with uncertainty and/or assistance		User was unsuccessful in completing social interaction task		Did not test

Overall, this user was very comfortable using the device to identify people as well as locate them in her space. Her user experience was rather similar to mine. However, she was much faster at both learning and adapting to the user interface. She really liked the idea of having the button to push so that we could hear the name of the persons in our surrounding. “Having this [pointing to the button] is so good. I would only want to know when [I] maybe enter a room” She was able to distinguish between the different proximity zones fairly well.

During the tasks, she performed well on all tasks and required no external assistance in maintaining and modulating a conversation as both the researcher and the potential interactor moved in the environment. However, there was some uncertainty in how she navigated the space. Because the device does not help the user navigate the space, they would still require some low tech to help them with this. In this case, she had her guide dog to help navigate.

For possible improvements, she suggested that the voice was speaking rather slowly and loudly. “The sounds could be fainter.” Additionally, she mentioned that having the vibrations and the sounds at the same time was like “saying the same thing twice”. She would have liked to have either the haptic notifications or the sonifications – and “have a button to switch between that”. We also discussed her concern of how it would be a distraction during a class. “Can I like switch it off when I’m in class?”.

Talking about the wearable, she said that it was still rather bulky and not really "fashionable", particularly because the headphones are very noticeable. She initially also had a little trouble moving around the space during the structured tasks initially, though, she used her dog to help navigate her surroundings. Generally, she said that the device would help her if she “did not know people in a new place”.

Sociability and Technological Comfort Pre-Post Results

Paired samples t-tests were conducted to examine the potential difference in sociability and technological comfort between before and after using the assistive device. (Figure 24) The user experienced a marginally significant ($p = 0.048$) improvement in sociability reported after the use of the assistive device ($M = 4.22$, $SD = 1.27$) compared to before the use of the assistive device ($M = 4.8$, $SD = 1.03$).

There was not, however, a significant change in the level of technological comfort after the use of the assistive device ($M = 4.63$,$SD = 1.03$) compared to before the use of the assistive device ($M = 4.80$, $SD = 1.03$; $p = 0.41$). In fact, each of the statements on the scale were scored the same way. This might be because the user already was comfortable with technology use as well as learning new technical skills. (Figure 25)

Overall, these tests showed that there was no change in the technological skills which remained high both before and after the interaction with the device. However, we noticed a slight improve-

Figure 24: Graph showing the user's level of sociability before and after use of Prototype 2

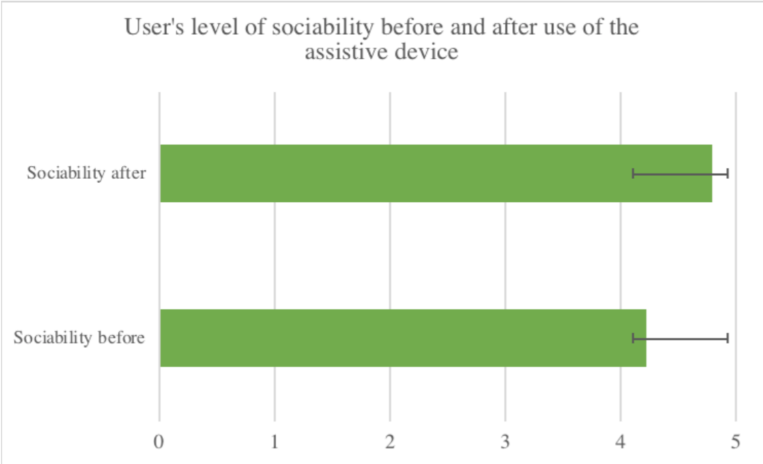
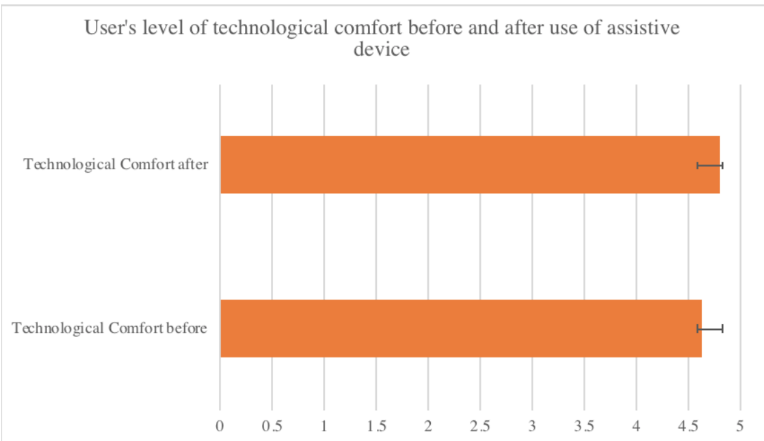


Figure 25: Graph showing the user's level of technological comfort before and after use of Prototype 2



ment in sociability levels after just a one-hour session with the device.

Insights gained

In summary, the device was able to perform its primary tasks of identifying people and letting the user know how far away the person is. The user interface was easy to learn, and intuitive. There was an additional need to possibly separate have different modes: possibly vibration mode and sonification mode or even have a temporary off switch for when in high focus tasks that do not require social interactions. There was also a marginally significant increase in the sociability levels of the user.

4.2.4 Usability Testing – User-Feedback Round 2

Figure 26: Diversity in Participant Sample

<table>
<tr><td colspan="2"><u>Late-onset blindness</u> (n=5)</td></tr>
<tr><td rowspan="4">Age-related macular degeneration (gradual loss of vision)</td><td>With Peripheral vision and no central vision</td></tr>
<tr><td>No light perception in one eye and degenerating vision loss in another</td></tr>
<tr><td>Along with Hearing Impairment</td></tr>
<tr><td>Along with Motor Nerve Degeneration</td></tr>
<tr><td colspan="2">Phantom Vision (sudden loss of vision)</td></tr>
</table>

Five participants (4 female, 1 male) were recruited from a retirement community and assisted care facility in the Pioneer Valley neighborhood. Participant ages ranged from 84 to 102 (M=96, SD=8.3). They had all experienced late-onset blindness: 4 of them are experiencing or have experienced gradual loss of vision due to age-related macular degeneration and 1 of them experienced sudden loss of vision due to a complication during cataract surgery causing phantom vision. Even though the 4 participants who experienced gradual loss of vision had the same cause for loss of vision and are classified as legally blind, they all had different experiences. One of them has no center vision but has good peripheral vision. Another participant is blind in one eye and is experiencing rapid vision degeneration in the other eye. The other participants have intersecting accessibility needs of not only being visually impaired, but also having hearing impairment and motor nerve degeneration. Their usability testing results are in Figure 27.

User Feedback from Think-aloud protocol

We met with the users for over a two-and-half-hour session. The users were able to recognize people in their surroundings even if they were far away and could not be seen or recognized at a

Figure 27: Usability Testing Prototype 2: Tracking Independence in Task Performance for 5 participants

User location and position	**Researcher Location and Position**	**Independence in social interaction tasks**				
		Participant 1	**Participant 2**	**Participant 3**	**Participant 4**	**Participant 5**
Constant position, sitting	Is standing within 3 feet distance of the participant (personal space)					
	Is standing within 10 feet distance of the participant (social space)					
	Is standing within 15 feet distance of the participant (public space)					
	Is moving between 3 feet and 10 feet distance from the participant					
	Is moving between 10 feet and 15 feet distance from the participant					
	Walks into the room and enters within 3 feet distance of the participant					
	Walks out of the room from standing before within 3 feet of the participant					
Is moving between 3 feet and 10 feet distance from the researcher	Constant position, sitting					
Is moving between 10 feet and 15 feet distance from the researcher						
Walks into the room and enters within 3 feet distance of the researcher						
Walks out of the room from standing before within 3 feet of the researcher						
The participant and the researcher are both moving such that they are approaching each other from being initially 10 feet apart						
The participant and the researcher are both moving such that they are moving away from each other after being initially 3 feet apart						
The participant and the researcher are both moving such that the participant enters the room that the researcher is moving around						
The participant and the researcher are both moving such that the participant exits a room in which the researcher is moving around						
The participant and the researcher are both moving such that the researcher enters into the room that the participant is moving around						
The participant and the researcher are both moving such that the researcher exits a room in which the participant is moving around						

distance. They were able to immediately use the device with minimal instruction suggesting that the device is easy-to-learn. I just had to demonstrate it to them once, and then they were even able to teach it to each other and perfectly explain the different features. The user interface did not seem to be overwhelming because it did not interfere in their conversations. If they wanted to know exactly who was there, they usually stopped speaking and pressed the button to hear the device speak but continued speaking regularly after. They also really liked that the headphone did not go into the ear but over it so that they could still hear other sounds from their surroundings.

During the social interaction tasks, there was some uncertainty of exactly where the potential interactor was when we moved in and out of the room. There was also a lag if the room was small and/or the potential interactor moved rather quickly through space. However, overall all were able to perform the tasks successfully with no additional support and only relying on the device. For a couple of participants with walkers and walking sticks it was easier to navigate the space than others. Any additional support provided was only with regards to either how to wear the device initially or how to navigate the space later.

They had some trouble putting on the strap of the wearable because it required a bit of dexterity and finding the right hole to put the pin of the strap into. This was hard to do because of not only the reduced vision aspect but also the motor complexity aspect. They suggested that I replace the strap with a "just a thick elastic band or Velcro could be easily snapped on". Another aspect of the wearable mentioned during potential improvements was that it is very bulky, particularly the headphones. Having something that they can wear around the ears "like earrings or for someone who does not wear earrings like [Male Participant], we can have something that goes over your glasses like an ear-piece behind the ear."

One of the users who is blind in one eye mentioned that it would be "helpful when there is further degeneration in the other eye" as well. As of now, he says, "since I am blind in this [left] eye, I would not have known who is there [points to his left field of vision] without moving my head completely so that my right eye could see. I can see a shape very indistinctly, but I would not know who it is if I was looking just straight ahead." "Normally, I would look. So, it would not be helpful currently. But, if my vision deteriorates over a period of time, I would be able to see it working well."

Another of the users who has low hearing as well as low vision said that, "it [the speech notification] was loud enough, but just not clear enough." "Boy, that was like boop boop boop. It is really loud!" When another participant with hearing impairment was asked "did you hear that?", they answered "Yeah! But I could not make it out at all." Therefore, we realize that it is not only important to make the notification loud, but also clear and well-spaced out. Another participant who wears hearing aids, mentioned that she could still hear everything fine. This suggests that the hearing aids and these headphones do not interfere with each other.

Additionally, some users mentioned possibly having just the vibration patterns because they did not need to be notified via sonifications in all environments and contexts. This seems to be consistent with our previous user study as well. However, one of the users with severe visual impairment and neuro-degeneration mentioned it was good to have both the sounds and the vibration patterns because if she missed the vibration pattern, she could still hear a sound notifying her.

Discussing overall thoughts about the device at the conclusion of our user-feedback session, they said it was a "cool device" that could easily be integrated into their daily routine. However, since many of them could already see rather well, they did not have an immediate need for the device. They said that the device was useful in helping them know of things that they would usually miss so that they are more aware than before. This would help them engage in conversations because they know more about the environment now than they did before. They also suggested many different applications in different contexts of their lives than just social interactions. One of the ideas was that, it could be a way for assistive care staff to locate a user in times of emergency. They also said that it could be used as an added security measure where they can immediately know who is knocking at their door when they are not expecting someone. Another use was an example of if they are walking by and they "see" someone near the puzzles area or near the gym, they could join them.

Sociability and Technological Comfort Pre-Post Results

Paired samples t-tests were conducted to examine the potential difference in sociability and technological comfort between before and after using the assistive device. There was no significant change ($p = 0.72$) in sociability reported after the use of the assistive device ($M = 3.60$, $SD = 0.50$) compared to before the use of the assistive device ($M = 3.04$, $SD = 1.12$) by all the participants. However, one of the participants who had the most severe age-related macular degeneration with very little light perception reported a significantly higher level of sociability after using the device. (Figure 28)

However, there was not a significant change in the level of technological comfort after the use of the assistive device ($M = 2.26$, $SD = 1.02$) compared to before the use of the assistive device ($M = 2.41$, $SD = 1.03$). This might be because many of the participants reported very low levels of technological comfort. However, if we look at one particular participant who had severe macular degeneration in one eye and another who had severe degeneration in both eyes, they reported that they would be willing to learn new technology if it helped their vision. They also said that this particular device did not require them to know any high-level technology, so they felt comfortable using it.(Figure 29)

Figure 28: Graph showing each of the user's level of sociability before and after use of assistive device

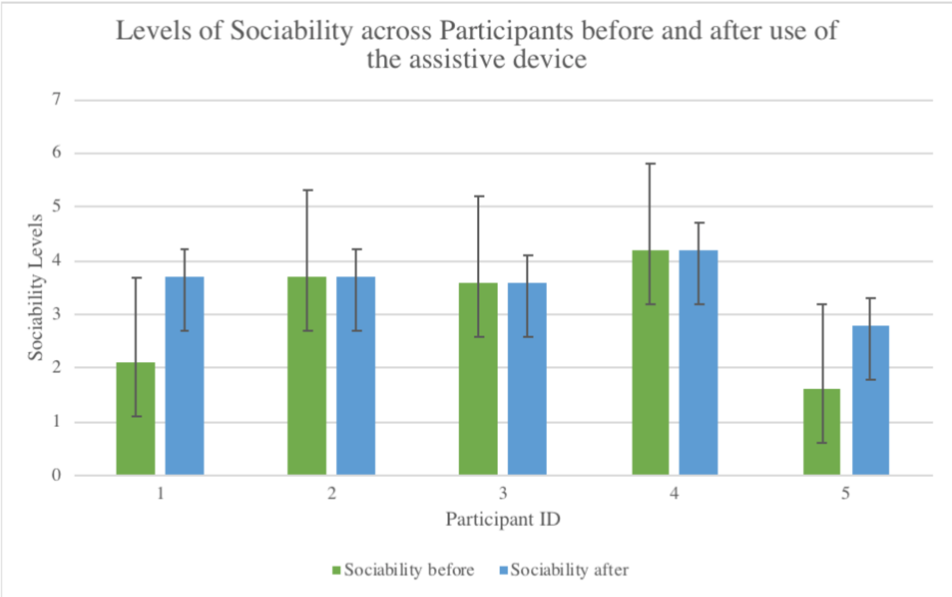
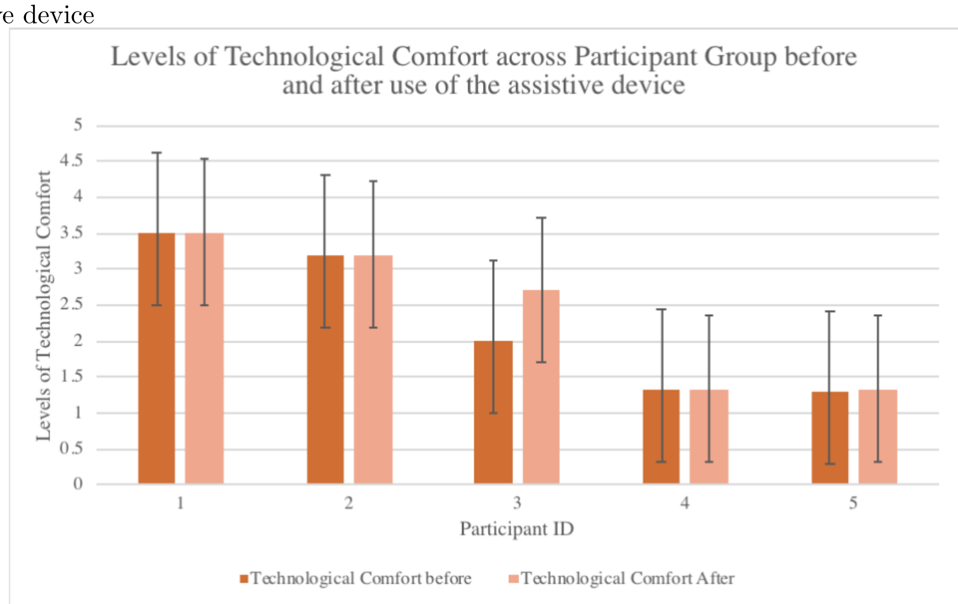


Figure 29: Graph showing each of the user's level of technological comfort before and after use of assistive device



Insights gained

In summary, prototype 2 - the single-purpose wearable device was able to perform its primary tasks of identifying people and letting the user know how far away the person is. The user interface was easy to learn, and intuitive. User feedback showed that we could maybe improve the design by adding different modes: possibly vibration mode and sonification mode or even have a temporary off switch for when the user is engaged in high-focus tasks and do not want to engage in social interactions. There was no significant change in the sociability levels or levels of technological comfort of the user during the short sessions we had.

4.3 Overall Results

We employed a systems approach to inform our understanding of the user experience and building assistive technology and user interface by pulling from literature in cognitive neuroscience, sociology and technology. We put together a list of potential user's requirements and product design requirements.

The first prototype's design was informed by the literature review and was designed to fulfill these product requirement. When we performed usability testing and gathered user feedback we realized that the biggest positives from the iPhone-based prototype design was that it was a low-energy, durable solution that identified and placed individuals accurately in the user's space. On the other hand, it was unintuitive, not easy-to-use and the user interface was rather cognitively overwhelming frustrating the user over a period of time.

Since the device was not as usable as we expected, we looked to the devices that the potential users used successfully everyday. We realized that most of these devices were reliable and easy-to-use because they were single-purpose devices and we adjusted our understanding of the user experience and product requirements based on these insights gained.

Our second prototype was a single-purpose wearable device that conveyed to the user only the significant changes in proximity through sonifications, haptic notifications and speech notifications. Upon performing multiple rounds of usability testing and gathering user feedback, we observed that it was successful in not only informing the user of the right information - identity and proximity of the potential interactors, but also was successful in doing it in an easy-to-use, intuitive manner.

Observing the results we have seen through this project, we notice some overarching trends. First, the device is increasingly helping the user engage in social interactions without any additional support. Generally, most users have moved from being in the maximal or moderate assistance category to the no helper or modified dependence category on the independence scale. This shows that the device does help users independently engage in social interactions. Second, the user feedback has been overwhelmingly positive in terms of whether it helped them know who is in

Figure 30: Comparing the two prototype designs against the user needs and product requirements

User Needs/Product Requirements	Prototype 1: iPhone-based design	Prototype 2: Single-Purpose Wearable design
Single-purpose device	(red)	(green)
Low-cost	(yellow)	(green)
Low-energy	(green)	(green)
Durable	(green)	(yellow)
Able to differentiate and map proximity zones fairly accurately (ranging within feet)	(green)	(green)
Able to identify individuals accurately and reliably	(green)	(green)
Independent of pre-existing architecture (e.g. Wi-Fi, Mobile signals, Satellite)	(green)	(green)
Intuitive i.e. integrates into existing behavior	(yellow)	(green)
Speech Notifications that only update the user when people have significantly changed their proximity to the user	(red)	(green)
Haptic Notifications that only update the user when people have significantly changed their proximity to the user	(red)	(green)
Sonifications that only update the user when people have significantly changed their proximity to the user	(red)	(green)

Legend:

(green)	Very Good (Ideal for our needs)	(yellow)	Good (Fits our needs fairly well)	(red)	Bad (Does not fit our needs at all)

their surroundings. The marginal improvement in sociability levels even after just a short period of use shows that this device might have the potential over a period of time affect confidence in their interaction patterns.

When compared with the iPhone design, there are two main things that the second design is not as good at. First, it is not as durable in its current iteration. If it falls or hits another surface, it is likely to break or not function properly. Second, this second design is not capable of parallel processing. Since it can only do serial processing, the device might have some lag in detecting multiple beacon data and reporting them all. Not only does this device have a processing limitation, it also has a memory limitation in that its memory is smaller than that of an iPhone. Therefore, the second iteration can save only a certain number of sounds and notification patterns. This sets a limitation on the number of people we can beacon and the user can recognize that does not exist in the iPhone design. This is not a major problem currently, though it may be a concern as we scale the environments and contexts we want to map.

5 Conclusions and Future Work

The main research question addressed in this thesis is: How can we design an easy-to-use, intuitive assistive device for the visually-impaired that helps them identify persons in their surroundings? By employing a systems approach that builds on our understanding of not only the technological background, but also the neuro-cognitive and social framework we developed different design prototypes to approach this problem. Then, we used user-feedback to guide further development such that the device could best help users interact more independently.

5.1 Lessons Learned

First, we learned more about the visually-impaired experience interacting with technology. While general human-computer interaction has been a topic that has been extensively studied by many disciplines, the visually-impaired or blind interaction with technology is a topic that is under-explored. As we are propelled into the fourth industrial revolution and an era of technology, this project expands on our understanding of how a large group in our population interacts with technology. This project identifies challenges and defines possible solutions to better the visually-impaired or the aging populations' experience with technology.

Furthermore, this project begins to lay down the foundation for designing possible intuitive haptic and audio user interfaces that benefit visually-impaired needs by understanding how they already interact with the world around them. We learned that it is easier and more intuitive for the visually-impaired to use single-purpose devices that they can definitely rely on for that single purpose. Instead of constant notification, only notifying them when there is a significant change in their environment or context works better. Having only one notification stream activated, either audio or haptic, at any given time helps augment their knowledge about their surroundings more effectively without overwhelming them.

Aspects of the design could also be used by other populations such as those with prosopagnosia – an inability to recognize faces, or those with depth perception problems, or even general memory issues. This should possibly help them approach others to engage in social interactions more confidently. Conversely, many aspects could also be translated into possibly designing intuitive multi-sensory user interfaces for the sighted.

5.2 Limitations

While the current prototype's results are encouraging, there are a few limitations to this solution. Firstly, there is some improvement that needs to be made with regard to accurately reporting significant changes in position in real-time. There is still some uncertainty in situations where the user is moving faster than the broadcasting or notification speed. For example, when a user presses the button when the potential interactor, Person A, is far, there will be a speech notification triggered which will say "Person A is far." However, if Person A has moved quickly from the far proximity zone to be immediately near the user before the speech notification has ended, this would be an incorrect notification. This is confusing because the user now believes that Person A is far, when in reality they are near. Possibly moving from the serial processing ESP32 board to a multi-thread processing system that can keep track of multiple information at the same time would help provide feedback in real-time. This is a limitation of the current prototype design.

Secondly, there is a trade-off between knowing who everyone in the surroundings is at any given point in time versus just knowing when a few important people are near you. In the current prototype design, it is computationally not possible to have more than about 3-4 people beaconed and detectable by the device. This is not a major limitation because it is also hard for the user to detect too many differences in notification patterns. It is especially hard to differentiate between haptic notifications because our sense of touch has a higher sensory threshold near the wrist. Furthermore, it will be harder for the user to resist sensory adaptation because not all the notifications will be as important. Also, if there are too many notifications, then it is hard to keep track of what each of them means or which ones are more important than the rest. Therefore, while this is not a major limitation because it would be cognitively overwhelming for the user, this limitation prevents this prototype device from scaling up to larger environments and contexts.

Thirdly, this is a rather bulky device. This is because we are pulling different capabilities and functionalities from different hardware resources. This is a major limitation to the current prototype. If we were to however engineer a board with Bluetooth transmitter and receiver functionality, micro-controller, sound storage, battery power it would be much simpler. We could also have the Bluetooth bone-conduction headphone designed to be much smaller. However, engineering a new board would be cost-effective only if we were to make this into a product and produce this at scale.

5.3 Challenges

There were many new challenges during this journey and through each challenge I learnt new things that I could not have learnt otherwise. The first challenge was finding users who were willing to provide their invaluable time and feedback for the successful development of this device. This entire process was very insightful, right from going through the IRB approval process to the insights gained from the users about each iteration of the design.

The second challenge was capturing the users' interaction patterns over a longer period of time. Would they actually give up their current assistive system (their friends and family) to actually incorporate this device into their routine? From our understanding and current user interaction, it seems that this device could be very useful for them to know when their "assistive" person is in the room. However, there is an aspect of trust and reliability built over a period of time in their interaction with the device that needs to be explored further.

5.4 Future Work

It is imperative that we continue to explore these questions regarding use of assistive technology over a longer time period. In the current user studies, we had the users use the device for less than an hour. This is a very short-trial period. Our observations show that they were able to successfully use the device to perform the structured social interaction tasks, that the device is easy-to-learn, easy-to-use and can help the user identify and place individuals on their cognitive map. However, we were not able to study how the device answers the larger issue of loss of sociability, independence, and life satisfaction. This is because these are personality traits that only change over a period of time. From our observations, all we can tell is that this device has potential to improve the sociability, independence, and overall life satisfaction since the users were positive about its potential. However, this is a big question that needs to be explored. How does the assistive device affect sociability, personality, overall life satisfaction of the user over a period of time. Also, how does the relationship between the user and device develop? Do we see a change in reliability and trust built over a period of time?

On the other hand, having preliminarily explored how the visually impaired create mental maps and having leveraged this information to create our current audio-haptic user interface, we can further explore the sensory thresholds, sensory adaptation mental imagery and mapping to design a better suited user interface based on different accessibility needs. For example, we could build different user interfaces for users with late-onset blindness and one for those with late-onset blindness and others for those with additional accessibility needs such as hearing loss or motor degeneration.

Moreover, we could also explore how we can customize to these different accessibility needs. One way would be to have the user do an initial set-up to calibrate user needs as well as contextual and environmental needs. Another way would be to build an intelligent user interface that learns the user's interaction patterns in different contexts and environments over a period of time and adapts accordingly.

In conclusion, having explored the cognitive and social basis of interaction and having built a technological solution that integrates into the user's existing schema, we are confident that many avenues of research will be informed by this thesis to create systems that intuitively interact with humans and improve their experience not only with technology, but also with other people in their surroundings.

Appendix A

Interview Guide/Meeting Agenda during User Meeting

- Introduce myself "Hi, I'm Srishti. I am a student researcher with Mount Holyoke College working on a project to help you easily recognize people you care about near you so that you can independently and confidently approach them to start a conversation. As a Computer Science and a Psychology researcher, I am interested in building a low-cost, easy-to-use device that can help you do this."
- Lay down expectations for this meeting: Today, I want to learn from your experiences that will inform the design of this device. 1. This is a safe space to share any ideas, concerns, thoughts about your experiences and the design of this device. 2. Please feel free to stop me and ask any questions when you have them 3. If you have any trouble hearing me or understanding me, please feel to stop and ask me to repeat myself at any point during this meeting
- First, I would like to make sure that we are all on the same page and get your permission that you agree to participate in this study by signing an Informed Consent. This is standard procedure for any study. Each of you has a copy of the informed consent that I will be reading out. Chris, and Maureen in addition to the Mount Holyoke College Institutional Review Board have reviewed and approved this study and the informed consent.
- Are there any questions for me before we delve into the questions?
- Now, I wanted to collect some general information about you, please share only if you feel comfortable sharing:
  I'd like to find out the extent of visual impairment and what kind of vision awareness do you have? (Legally blind with light perception,Legally blind without light perception, Peripheral vision, low vision)
  When did you experience vision loss - was it earlier in your childhood or was it later in life? Early-onset or late-onset blindness?
  How long have you had vision loss? Duration they have experienced vision loss
- Let us talk about any technology assistive or otherwise that you use currently:
  Do you currently use any assistive technology? If so, which ones?
  many of you use (this technology)? (Repeat for all technology used currently)
  What do you use it for?
  How do you use it?
  How satisfied are you with your current experience with (this technology) on a scale of 1 =

not satisfied at all to 5 = highly satisfied? Please explain your rating

What features do you like about (this technology)? Make it easier for you to use? Or make you happy?, What features upset you about this (this technology)?

Any improvements that you would suggest

- Now, let us shift gears and talk about any technology assistive or otherwise that you used in the past:

  Have you used any other assistive technology in the past to help with vision loss?

  How many of you use (this technology) or have used it in the past? (Repeat for all technology used currently)

  What did you use it for?

  How did you use it?

  Why did you stop using it? (E.g. Wasn't easy to use, it was not reliable, it was glitch, it was not engaging enough)

  How satisfied are you with your current experience with (this technology) on a scale of 1 = not satisfied at all to 5 = highly satisfied? Please explain your rating

  What features do you like about (this technology)? Make it easier for you to use? Or make you happy?

  What features upset you about this (this technology)?

  Any improvements that you would suggest

- Now, let us discuss the design of this new assistive device. I can go through some of the features that we are currently thinking about and would like your thoughts on these:

- Wearable?

  Would you like it if it is wearable? Do you expect it to be wearable? Do you dislike it?

  Low cost?

  How low cost would you like it to be?

  How much time would you be willing to put in to learn the use of this new device?

  How wear resistant would you like this to be? Would you like it to be water-resistant?

  What other features would you like to see in this?

- "Thank you so much for sharing your thoughts, insights and experiences with me. I will go back and integrate what we have discussed here today into design of the device model."

Appendix B

Structured social interaction tasks to understand whether the device affects sociability

Task 1: Instruction to participant: Maintain a normal conversation with the researcher. While the researcher:

1. (a). Is standing within 3 feet distance of the participant (personal space)

1. (b). Is standing within 10 feet distance of the participant (social space)

1. (c). Is standing within 15 feet distance of the participant (public space)

1. (d). Is moving between 3 feet and 10 feet distance from the participant

1. (e). Is moving between 10 feet and 15 feet distance from the participant

1. (f). Walks into the room and enters within 3 feet distance of the participant

1. (g). Walks out of the room from standing before within 3 feet of the participant

Task 2: Instruction to participant: Maintain a normal conversation with the researcher. While the researcher is sitting down and the participant:

2. (a). Is moving between 3 feet and 10 feet distance from the researcher

2. (b). Is moving between 10 feet and 15 feet distance from the researcher

2. (c). Walks into the room and enters within 3 feet distance of the researcher

2. (d). Walks out of the room from standing before within 3 feet of the researcher

Task 3: Instruction to participant: Maintain a normal conversation with the researcher. While the participant and the researcher are both moving such that:

3. (a) They are moving towards each other from being initially 10 feet apart

3. (b) They are moving away from each other after being initially 3 feet apart

3. (c) The participant enters the room that the researcher is moving around

3. (d) The participant exits a room in which the researcher is moving around

3. (e) The researcher enters into the room that the participant is moving around

3. (f) The researcher exits a room in which the participant is moving around

Appendix C

Sociability measure from the Preliminary International Personality Item Pool (IPIP)'s California Psychological Inventory (CPI)

On a scale of 1-5 rate these from how well the statement describes you where *1=Does not describe at all* to *5=Describes me completely*

- Feel comfortable around people
- Act comfortably with others.
- Am skilled in handling social situations.
- Talk to a lot of different people at parties.
- Start conversations
- Often feel uncomfortable around others.
- Have little to say.
- Find it difficult to approach others.
- Have difficulty expressing my feelings.
- Only feel comfortable with friends.

Appendix D

Acquisition of Technical Knowledge scale

- I spend time experimenting with programs I don't know very well in order to increase my knowledge.
- I take advantage of any situation where I can learn more about computers, the Internet, and other information technology.
- I skip over newspaper or magazine articles that deal with computers and other technologies. (R)
- If I have a problem using the computer, printer, fax, etc., I know where to seek help.
- My supervisor or instructor will keep me up-to-date on the latest technologies. (R)
- I use the "help" feature included with programs to help me learn how they work.

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