"Who's There?": A Wearable Device to Help Visually Impaired Users Identify Others

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ABSTRACT

Approximately 4% of our world's population is visually impaired, and more than half of them are over age 50. Visual impairment often leads to a loss in independence and diminished sociability, which in turn reduces life satisfaction. Based on observations and interviews of visually-impaired individuals, we identified three specific problems: difficulty recognizing people in their surroundings; inability to proactively greet others entering their social space; and trouble identifying if people are within hearing range as they move around during interaction.

In this paper, we present a wearable bracelet that uses audio-haptic communication to help visually impaired identify people and their locations. It is a first step towards an intuitive low-cost device that can potentially benefit not only the visually-impaired but also people with memory challenges or difficulty recognizing faces.

CCS CONCEPTS

• **Human-centered computing** → **Accessibility technologies**; *Ubiquitous and mobile devices*; • **Social and professional topics** → *People with disabilities*;

KEYWORDS

Visually-impaired, Assistive Technology

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1 INTRODUCTION

Approximately 4% of the world's population has a reduced ability to see that cannot be cured by standard corrective measures such as glasses or even surgery. Loss of vision is one of the most common problems that arises as we age. 65% of visually impaired are over age 50. Furthermore, an estimated 90% of them live in low and middle-income countries[1]. With an increasing elderly population in many countries, the number of visually impaired will rise dramatically in the coming years.

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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 [9, 10, 12]. A lack of social interaction for older adults may contribute to higher rates of disability, slower rates of recovery from illness and even early death [4, 34].

Observing and interviewing visually-impaired people and their family and friends, we identified three specific problems that they face while communicating with others independently:

- 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.

Our goal in this research project is to design an assistive device for the visually impaired that helps them identify and place persons in their surroundings such that it increases their sociability and independence.

Most of the work done so far in the technological research community to support the independence and social inclusion of the visually impaired is done by enabling smoother navigation. While technologists continue to work 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 has been no significant research done towards recognizing and placing other people in the user's dynamic environment where both the user and potential interactors are constantly moving. Developing an intuitive solution to this problem requires not just developing the technology, but also understanding this as a cognitive and social problem, where the solution must organically add to the mental and social schemas already learned by the blind user.

In this project, we approached this socio-technical problem by employing a systems approach to understand the cognitive, social and technical sides and then built a focused solution using a user-centered design approach.

Using the iterative user-centered design process, we developed two distinct prototypes with several iterations of the design-thinking process. The first relied on an iPhone to notify the user of who was where in their surroundings through designated sonifications, speech notifications, and vibro-tactile haptic notifications. While it performed the tasks, it was too cognitively overwhelming, frustrating and exhausting for a blind user because of the phone's many notifications and functions. Therefore, it was ineffective in organically augmenting their perception of who was in their surroundings.

In this paper, we present a three-fold solution: 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 research contributes to the growing literature in the field of not only assistive technology, but also multi-sensory augmentation in human-computer interaction overcoming the challenges of socio-technical research. Secondly, it expands on our understanding of the visually-impaired user experience with technology and its pain points so that we can build more intuitive technology for this significant population. Thirdly, it presents a foundation for designing audio-haptic interfaces and devices for not only visually-impaired, but also for those with other age-related problems such as memory loss (dementia), trouble recognizing faces (prosopagnosia) or even problems with depth perception.

In Section 2, we describe related work in assistive technology design and understanding the users' cognitive, social and technological needs. Section 3 describes the hardware and software design of the wearable device. Setion 4 describes our methods in evaluating user needs and usability of the system. Section 5 discusses the results of usability testing and user feedback. We conclude in Section 6 with a discussion of the lessons learned, limitations and future directions.

2 RELATED WORK: UNDERSTANDING VISUALLY-IMPAIRED USERS' NEEDS

Understanding Existing Assistive Technology

Assistive technology has been extensively researched and created for both outdoor and indoor navigation by identifying objects, barriers and, entryways, including [7, 11, 17, 21, 27, 29, 38]. While outdoor systems rely upon GPS to locate the user [27, 29, 32], indoor systems typically rely upon physical augmentation of the environment such as ultrasound [7, 37, 41], Wi-Fi access points [14, 36], radio frequency identifier (RFID) tags [11, 31, 43] or expensive sensing equipment such as computer vision [15, 38] or integrated systems modeling the input from a combination of these [44].

Since we want to make this device as usable as possible, we need it to be a low-cost, low-energy system that can flexibly map surroundings and reliably identify people with as little need for pre-existing architecture as possible. These requirements eliminate the possibility of using the technology described above.

There are a few 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, 13]. NavCog built by a team led by Dragan Ahmetovic at Carnegie Mellon University [3] is a low-cost low-energy mobile application 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. While its focus is still on avoiding static objects during navigation rather than social interaction, it demonstrates the use of low-cost, low-energy equipment in navigation.

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 [17]. 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 with whom the user could engage.

Overall, 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 making it different and more dynamic. Furthermore, what is distinctive about our system is the simplicity of a simple wearable enabling the creation of a dynamic socio-semantically rich mental map.

Understanding How Visually Impaired Users Create Mental Maps

In order to augment the blind user's perception of who is in their surroundings, we need to first understand how their mind perceives and processes the space around them. Most of the information required for mapping is gathered through the visual channel [28]. In the absence of this visual information, the blind adapt to create mental maps through compensatory sensory channels such as touch, sound and even language [5, 18, 19, 23, 25, 33, 39]. This phenomenon is known as *cross-modal plasticity*[5].

The blind develop cross modal plasticity to reroute auditory and tactile information to create mental imagery and maps of their surroundings. There are certain differences in how cross modal plasticity develops. Congenitally blind individuals or individuals with early-onset blindness are more perceptive to changes in the auditory and tactile cues, which enables them to create more accurate mental maps than those who experience late onset blindness [35].

With our audio-haptic user interface, we hope to intercept and augment the neural processing pathways, that would usually process visual cues to detect where objects are in space and analyze their movement, with auditory and tactile cues that should create the same perception in the visually-impaired user's brain. Current work to develop intuitive user interfaces builds on this information by employing either speech notifications, sonifications or haptic notifications. Speech notifications are essentially talking signs attached to static objects. Sonifications are used to help map the environment by associating different materials or objects with differences in frequency, amplitude or timbre of the sound [8, 30, 42]. The use of haptic user interfaces is more recent and is used by tactile graphic displays by modulating the pressure and frequency to create a recognition [6, 22]. However, haptic interfaces have very low resolution because it is hard to differentiate between and learn too many haptic cues [22].

Understanding Use of Interpersonal Space

To understand the social aspect of how we use the space around us to interact with people we look at the interpersonal space model proposed by Edward Hall in 1963 [16] as illustrated in Figure 1. This models states that the way we interact with people changes depending on how far away they are from us and classifies interpersonal space into four distinct zones: (i) intimate space, (ii) personal space, (iii) social space, and (iv) public space.

Intimate space, within about 1.5 feet, is generally used for confidential or really close interactions such as embracing, touching or whispering. Personal distance, 1.5 to 4 feet, is generally only entered by close friends and family. Social space, 4-12 feet, is the distance at which other people are generally acknowledged and greeted. These might be people who are in the same room or walking down the hallway, but who are not engaged in a long conversation. Lastly, there is the public space, where other people are present but not generally interacted with, such as at a public gathering like a concert.

Understanding Technology Used Every Day

Based on the technological literature review and our understanding of the social and cognitive background we developed an initial prototype that was an iPhone application. The

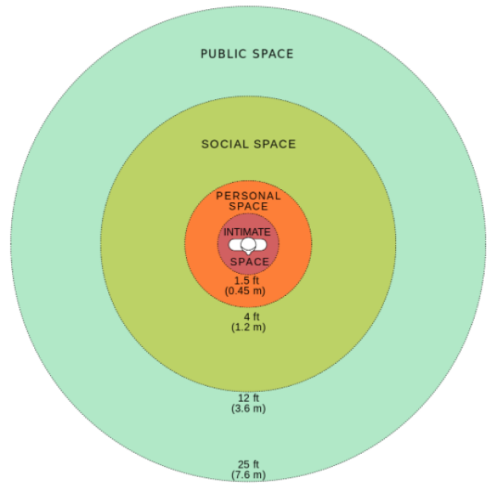

Figure 1: Interpersonal Space model by Hall

iPhone notified the user of who was where in their surroundings through speech notifications, sonifications and haptic notifications. The application could detect and keep track of multiple people in the user's surroundings. In evaluating this prototype with a participant who had experienced late-onset blindness and had no light perception, the user found the device to be unintuitive and cognitively overwhelming. This was because the same device, the iPhone, was not only notifying the user of where others were in their space, but also notifying her of phone calls, texts, and other information, and they all had different user interfaces to deal with the notifications.

In a short interview afterwards, we attempted to understand what devices she used successfully every day. We made three observations:

- The iPhone, even with the use of Siri and Voice Over, was very difficult to use effectively.
- If there is more than a single purpose to a device, these features and use cases are likely not going to be used, as shown by the Victor Reader[1], which can be used to place bookmarks and record messages, but the device is overwhelmingly used to read books and other publications out loud.
- Single-purpose devices, like the Color Teller[2] used to help a blind person identify colors of clothing, are easier-to-use, intuitive, and used frequently.

[1] https://store.humanware.com/hus/victor-reader-trek-talking-book-player-gps.html
[2] http://www.brytech.com/colorteller/

From this, we concluded that visually-impaired users are open to ideas and technologies to make them more independent, but that these must be carefully designed to be useful.

3 IMPLEMENTATION OF THE SYSTEM TO IDENTIFY PEOPLE

Product Requirements

While we were encouraged by these insights, we also realized that we had to completely revamp our design and move away from the cognitively overwhelming iPhone-based design and develop a single-purpose, wearable device. Thus, we updated the product requirements to accommodate our expanded understanding of the user experience:

- Single-purpose device
- Low cost
- Low energy
- Durable
- Able to differentiate and map proximity zones accurately to within a few feet
- Able to identify individuals accurately and reliably,
- Independent of pre-existing architecture (such as, WiFi, cellular signals, or satellite)
- Intuitive
- Smooth integration into existing user behavior
- Able to notify the user using three different mechanisms: speech, haptic, and sonification
- Notifications occur only when people have significantly changed their location in the user's surroundings
- User control over when speech notifications occur

User Experience

Our solution, determined after semi-structured interviews with potential users, is threefold: building a smart environment; designing a wearable bracelet with sonification and vibro-tactile communication; and creating a novel audio-haptic user interface. The environment consists of non-static, moving objects such as people and pets. The user wears 2 things: first the bone-conduction headphone worn over the back of the user's head that serves as the audio interface, and then second we have the bracelet which serves as the vibro-tactile haptic interface. Family or friends (potential interactors) carry a beacon that can be on them at all times - like a nametag, in their purse, or on a key fob.

When a potential interactor walks into their social space, they will be notified by a faint tapping on their wrist and a faint sound in their ears. As the person comes into their personal space, the tapping and the sound would become more frequent and insistent letting the user know that someone is there. To find out who it is, they press a button on the bracelet - and it will say the person's name and how far they are - like "Anna is near, Bob is far". Figure 2 shows an overview of the design and Figure 3 shows a user (third from left) using the device while interacting with friends and retirement facility staff (wearing beacon).

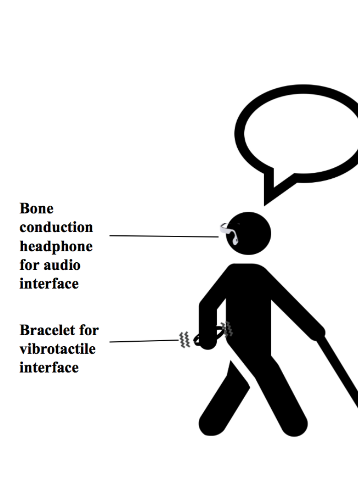

Figure 2: Interaction between user and other people in their surroundings

Figure 3: A user interacting with friends and staff while using the device.

Bluetooth Low Energy Beacons

To address the issue of identifying and placing moving persons in our environment, we use low-cost Estimote[3] Bluetooth Low Energy beacons. People in the environment wear or carry the beacons. In software, we map beacon ids to names of the assigned people. In this way, beacons serve the same purpose as nametags do for a sighted person. They broadcast their wearer's identity as a signal that can be

[3] https://estimote.com/

picked up by the user's Bluetooth signal receiver to know who the person is.

Additionally, the beacons report distances with an accuracy that enables us to map to the distinct interpersonal proximity zones fairly well, allowing us to differentiate between people in the personal, social and public space of the user, so that information can be communicated to the user along with the identity. Figure 4[4] shows what a Bluetooth beacon looks like.

Figure 4: Bluetooth beacon

The Wearable Device

Inspired by the talking wristwatch worn by our users, we decided to embed our single-purpose device in a wrist-based wearable. This wrist bracelet holds the Bluetooth receiver and transmitter, processing and memory unit, a vibro-tactile interface, and a button to control speech notifications.

It has a counterpart Bluetooth bone conduction headphone which serves as the audio interface providing both speech notifications and sonifications. We chose to use a bone-conduction headphone so that we can provide audible notifications without requiring the user to wear earbuds that would block sound coming from the environment, which is important for the user to build their mental map of the environment. The bone-conduction headphone also ensures a level of privacy since the sound is transmitted by vibrations through facial bones into the inner ear, and thus not audible to others nearby.

Figure 5 shows the device being worn, Figure 6 shows the internals of the device, and Figure 7 contains the schematic.

For the primary processing and memory unit, we use the ESP32 chip as it is a small board with a built-in Bluetooth module that fits well on the user'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.

Figure 5: Wearable

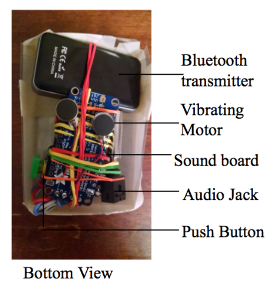

Figure 6: Wearable internals

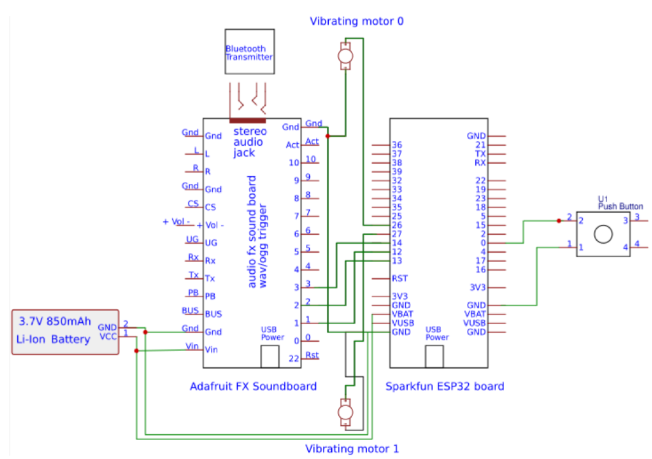

Figure 7: Wearable schematic

[4]http://www.businessinsider.com/beacons-and-ibeacons-create-a-new-market-2013-12

To enable sonifications and speech notifications, we use the Adafruit FX Soundboard, which is about 1.9" x 0.85". It can store about 2MB worth of sound and can be powered by a 3-5V Lithium-Polymer battery. It has 11 triggers, enabling us to notify the user of 11 different events with different sounds. Since each user has 4 sounds (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 relatively easy to learn to differentiate between and keep track of about 10-11 sounds [2, 20, 40]. 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 three proximity zones: immediate (personal), near (social) and far (public). The sounds become louder and higher in pitch when the person is closer to the user. 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. There is no sonification for far, only immediate and near.

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 bone conduction headphone, which is placed on the user's cheek bones. There is no vibration pattern for far, only immediate and near.

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 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 building this device was about USD115, broken down as: $20 for the Adafruit Sound Board, $20 for the ESP32, $5 including the audio jack, motors and the casing, $50 for the Bluetooth bone-conduction headset, $50 for 3-4 Bluetooth Low Energy beacons, and $20 for the Lithium-Polymer battery. However, this is just the prototype cost but in general when embedded systems are mass produced then it is possible to bring the cost down drastically to tens of dollars [26].

Software Implementation

Having discussed the hardware and the interface, now let us discuss how the software was developed. 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++.

We used the Eddystone URL BLE protocol to give maximum flexibility as Eddystone URL packets can be received and processed by any Bluetooth receiver.

We developed an algorithm for ranging the beacons and classifying them into the different proximity zones. When BLE beacons's Eddystone URL packet is received by the ESP32 board (that is, a person is detected nearby), the program notes the unique identity (URL) of the beacon and begins ranging.

First, to determine proximity zone based on the Received Signal Strength Indication (RSSI), 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.

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 in near real-time. Therefore, the user is notified shortly after the signal is received from the beacon. While the sonifications and the haptic notifications are reported to the user in near real-time, the speech notifications are only reported when the user asks to know exactly who is in their surroundings. There is a push button on the bracelet 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. If there are multiple people in the user's surroundings, the potential interactors are announced in a nearest to farthest order. The user interface only notifies the user when there is a change from the previous state. The program stores the information from the past three scans and only reports if there is a significant change in the proximity zone during this time. This is to prevent overwhelming the user with a constant stream of notifications, which could interfere with conversations or other activities the user is engaged in.

4 METHODS

As part of the user-centered design approach, surveys and semi-structured interviews were used to understand and identify explicit user needs and wants. 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 implemented in the prototype. We analyzed 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 in Section 5 by quoting these words and phrases and then presenting the assimilated insights from these diverse perspectives.

We also employed the Think-Aloud Protocol to evaluate user feedback during usability testing and gain insight into the users' cognitive processes, comfort levels and feelings while they interact with the device and perform various structured social tasks. 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 through different proximity zones. We used a rubric to track the users' independence in engaging with social tasks while using the device. This rubric was inspired by the Functional Independence Measure [24] usually used to evaluate the functional status of patients undergoing a rehabilitation following injury or operation.

Lastly, we briefly interviewed the users at the end of the usability testing, so that they have another opportunity to assimilate their feedback and experience.

5 EVALUATION

We evaluated the many iterative prototypes developed through the design thinking process. For our second prototype, and current solution, we worked with two distinct groups of potential users: those who experienced early-onset blindness in round 1 and adult/late-onset blindness in round 2. These participants were carefully chosen to represent the diversity in vision loss experiences and accessibility needs. The results from these usability studies and user feedback sessions are described in this section.

Usability Testing & User Feedback Round 1

Participant. We first collected user feedback from a 20-year-old legally blind female undergraduate student with no light perception who had experienced **early-onset blindness** and was blind with little to no light perception. She had a guide dog to help her navigate the space.

Usability Study. The social interaction tasks took place in an empty classroom. She interacted with the device for the usability study over the period of an hour.

Participants (N=6)	
Round 1: Early-onset blindness (n=1)	
Round 2: Late-onset blindness (n=5)	
Cause of vision loss:	Notes about intersecting needs:
Age-related macular degeneration (gradual loss of vision) (n=4)	with no center vision only Peripheral light perception (n=1)
	No light perception in one eye and degenerating vision loss in another (n=1)
	Hearing Impairment (n=2)
Phantom Vision (sudden loss of vision) (n=1)	Along with Motor Nerve Degeneration (n=1)

Figure 8: Diversity in Participant Sample

This user was comfortable using the device to identify people as well as locate them in her space. She quickly learned and adapted to the user interface. Using the device she was able to successfully maintain and modulate her conversation based on the proximity of the interactor.

User Feedback. She liked the idea of only having the identities announced when she pushed the button "*Having this [pointing to the button] is so good. I would only want to know who is in when maybe entering a room*"

For possible improvements to the user interface, she suggested that the voice was speaking 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 suggested having either haptic notifications or sonifications and *"have a button to switch between"*. We also discussed her concern of how it would be a distraction during a class. *"Can I like switch the sounds 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, 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"*.

Usability Testing & User Feedback Round 2

Participants. Five participants (4 female, 1 male) were recruited from a retirement community and assisted care facility in Massachusetts. Participant ages ranged from 84 to 102 (M=96, SD=8.3). They had all experienced late-onset blindness: four experiencing or having experienced gradual loss of vision due to age-related macular degeneration. On the other hand, one had experienced sudden loss of vision due to a complication during cataract surgery causing phantom vision. All were legally blind. These participants were carefully chosen to represent the diversity in vision loss experiences and accessibility needs.

All participants had varied experiences adapting to their adult-onset blindness. For example, one of them has no center vision but has good peripheral vision. On the other hand, another participant is blind in one eye and is experiencing rapid vision degeneration in the other eye. Similarly, three of the participants have intersecting accessibility needs of not only being visually impaired, but also having hearing impairment and motor nerve degeneration. Table 8 summarizes the participants.

Usability Study. The users were able to identify people in their surroundings who they otherwise would not have been able to, relying only on the device. Any additional support provided was only with regards to how to wear the device initially. Furthermore, they were able to immediately use the device with minimal instruction suggesting that the device is easy to learn. After a quick demonstration, 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.

There was some uncertainty when potential interactors moved in and out of some rooms. Since the device announces only proximity of the potential interactor, they could be 'near' but still behind a wall or door of a smaller room. There was sometimes a lag if the room was small and/or the potential interactor moved rather quickly through space. This suggests a need for calibrating the device to different environments and contexts.

Table 1 summarizes the results from the usability testing. In this table, a check mark (✓) means the user completed the social interaction task successfully and independently (i.e. without assistance from anyperson or thing other than the device itself), and an asterisk ($*$) means it was successful with some uncertainty and/or assistance from another individual. In all cases the users were successful in maintaining a social conversation during the task.

User Feedback. In conversations with the participants, we learned things beyond the social interaction tasks we asked them to do. One of the users who is blind in one eye mentioned that it would be *"more 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."* 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.

Giving feedback on the wearable, they talked about trouble putting on the strap of the wearable. This was hard not only because of their reduced vision, but also because the motor dexterity required. They suggested that we replace the strap with *"a thick elastic band or Velcro [that] could be easily snapped on"*. Another aspect of the wearable mentioned during potential improvements was that it is 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."*

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. On the other hand, 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 an "*interesting device*" that could easily be integrated into their daily routine. Even though many of them had some light perception, they said that the device was useful in making them more aware of other people who they would have otherwise missed. This would help them engage in conversations because they know more about the environment now than they did before.

They also suggested other applications of this device in different contexts of their lives than just social interactions. One of the ideas was 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 that if it made them aware of someone near the puzzle area or near the gym, it would be easy to join them.

Even though the participants did not usually feel comfortable using technology, 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.

User Position	Potential Interactor Position	Distance	Independence in social interaction tasks				
			User 1	User 2	User 3	User 4	User 5
Sitting	Standing	< 3 feet (personal space)	✓	✓	✓	✓	✓
	Standing	~10 feet (social space)	✓	✓	✓	✓	✓
	Standing	~15 feet (public space)	✓	✓	✓	✓	✓
	Moving	3-10 feet (between personal & social space)	✓	✓	✓	✓	✓
	Moving	10-15 feet (between social & public space)	✓	✓	✓	✓	✓
	Enters room	Stops at < 3 feet	∗	✓	∗	∗	✓
	Exits room	Starts at < 3 feet	∗	✓	∗	∗	✓
Moving	Sitting	3-10 feet (between personal & social space)	✓	✓	✓	✓	✓
Moving	Sitting	10-15 feet (between social & public space)	✓	✓	✓	✓	✓
Enters room	Sitting	Stops at < 3 feet	✓	✓	✓	✓	✓
Exits room	Sitting	Starts at < 3 feet	∗	✓	∗	✓	✓
Moving	Moving	Approach from 10 feet	✓	✓	✓	✓	✓
Moving	Moving	Depart from 3 feet	✓	✓	✓	✓	✓
Enters room	Moving		✓	✓	✓	✓	✓
Exits room	Moving		∗	∗	∗	✓	✓
Moving	Enters room		✓	✓	✓	✓	✓
Moving	Exits room		✓	✓	✓	✓	✓

Legend: ✓ Very good ∗ Good

Table 1: Usability Testing of Prototype 2: Tracking the Independence in Task Performance for 5 users who experienced late-onset blindness

Insights gained

In summary, 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 help personalize 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 does not want to engage in social interactions.

6 CONCLUSIONS AND FUTURE WORK

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 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 underexplored. As we are propelled into the fourth industrial revolution and an era of technology, this project expands on our understanding of how a significantly 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.

2. Single purpose assistive technology is more reliable and intuitive This project begins to lay down the foundation for designing possible intuitive haptic and audio user interfaces that benefit the visually-impaired 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.

3. Expanding the user-base to other age-related problems Since this multi-sensory design interface conveys the identity and location of potential interactors in a dynamic space intuitively, aspects of the design could also be used by other populations who cannot recognize, recall and/or keep track of information in space. Some examples of such user populations are: persons with prosopagnosia - an inability to recognize faces, or those with depth perception problems, or even memory problems such as dementia. This should possibly help them approach others to engage in social interactions more confidently. Similarly, many aspects could also be translated into possibly designing intuitive multi-sensory user interfaces for the sighted.

Limitations

While the current prototype's results are encouraging, there are a few limitations to this solution. The most significant challenge has been to improve system performance by reducing latency and processing delays because the user and/or other are moving constantly. There is still some uncertainty in situations where the user is moving faster than the broadcasting or notification speed. For example, if 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. We expect that 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.

Another limitation of the current design is an inability to scale the system without cognitively overloading the user. We can either create and communicate a map of everyone in their surroundings *or* just those 'important' to the user. In the current prototype design, it is computationally not possible to have more than about 3-4 people beaconed and detectable by the device. 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.

Finally, this is a 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, however, if we were to engineer a custom 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.

Future Work

It is imperative that we continue to explore these questions regarding use of assistive technology over a longer time period. This is a very short-trial period. Our observations about how users were able to successfully use the device to perform the structured social interaction tasks only shows that the device is easy-to-learn, easy-to-use and can help the user identify and place individuals on their cognitive map. 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. This is a big question that needs to be explored. How does the assistive device affect traits that take longer to alter such as: sociability, personality and 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 between the user and the device?

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, users with early-onset versus late-onset blindness might benefit from different user interfaces. Similarly, some users also need accommodation for hearing loss.

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 this technology can play a vital role in improving the experience of visually-impaired users and their interactions with other people in their surroundings.

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