Understanding In-Situ Use of Commonly Available Navigation Technologies by People with Visual Impairments

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ABSTRACT

Despite the large body of work in accessibility concerning the design of novel navigation technologies, little is known about commonly available technologies that people with visual impairments currently use for navigation. We address this gap with a qualitative study consisting of interviews with 23 people with visual impairments, ten of whom also participated in a follow-up diary study. We develop the idea of complementarity first introduced by Williams et al. [53] and find that in addition to using apps to complement mobility aids, technologies and apps complemented each other and filled in for the gaps inherent in one another. Furthermore, the complementarity between apps and other apps/aids was primarily the result of the differences in information and modalities in which this information is communicated by apps, technology and mobility aids. We propose design recommendations to enhance this complementarity and guide the development of improved navigation experiences for people with visual impairments.

CCS CONCEPTS

• Human-centered computing~Accessibility~Accessibility technologies

KEYWORDS

Visual impairment, navigation technologies, accessibility.

1 Introduction

There are 1.3 million people who are blind in the U.S. [18]. Many of these people experience mobility challenges that impede their ability to engage in everyday activities, limiting access to employment and social participation [34]. To work around these challenges, people with visual impairments use a variety of technologies. Low-tech navigation aids (white canes, guide dogs, and/or sighted assistance) remain foundational for facilitating orientation and mobility (O&M), but increasingly, mobile technologies that can assist with aspects of navigation have become widely available (e.g., [49]). While navigation and outdoor wayfinding have been of long-standing interest to communities at the intersection of HCI and accessibility, research here has primarily resulted in the design and evaluation of novel research prototypes. Though some work examining the navigation practices and technologies commonly used by people with visual impairments to get around has been done (e.g., [29, 53]), much of this research was conducted at a time when the technological landscape was significantly different than it is today. We asked the following research questions to examine these practices in the context of the current technological landscape:

1. What are the commonly available navigation technologies currently used by people with visual impairments? What factors into preferences for various technologies?
2. How are these technologies used? How do they work with low-tech navigation aids like white canes and guide dogs?

3. What are some of the gaps inherent in these technologies and are there opportunities to enhance the navigation experience of people with visual impairments?

To answer these questions, we designed and implemented a qualitative study with 23 people with visual impairments. Through in-depth, semi-structured interviews and a week-long diary study, we found that participants use an assortment of mainstream (i.e., technologies not specifically designed for people with visual impairments) and assistive technologies to aid navigation before, during, and after their journey. We confirm findings from prior research [53] which suggest that apps and technologies are useful to the extent that they complement participants' O&M skills and their use of low-tech navigation aids. We then extend this line of work to better understand the complementarity between navigation technologies and its impact on navigation for people with visual impairments. Specifically, our contributions in this paper include:

1. An in-depth examination of how complementarity between navigation technologies impacts the navigation experience of people with visual impairments. Additionally, we highlight several scenarios where technologies present information that contradicts that from other apps or mobility aids, presenting a challenge for our participants.
2. An analysis of how novel technologies that have only recently become widely available/used, like visual interpreter tools (e.g., Aira [4] and Be My Eyes [8]), are used to complement navigation skills to get around.
3. Recommendations and discussion for new technologies and designs that can enhance "complementarity" and thereby the navigation experience for people with visual impairments such as 1) considering the multiple dimensions of accuracy and complementary mobility aids (like guide dogs) in the design of navigation-related tools; 2) emphasizing the importance of easy switching between complementary apps. In addition, we also discuss how design might improve the accessibility of existing mainstream navigation apps like Google Maps (e.g., through the inclusion of text-based descriptions of landmarks/POIs) and voice-based services like Siri (e.g. through the provision of more contextually relevant location information)

2 Related Work

Our study builds on prior research on navigation technology for people who are visually impaired, including work on developing and evaluating novel navigation technologies, and work investigating navigation practices. While prior work includes technologies to support both indoor and outdoor wayfinding, most indoor navigation systems remain experimental, relying on RFID tags, Bluetooth beacons, and other means for localization (e.g., [15, 16, 20, 54]). The only systems currently in widespread use are for outdoor navigation, so we limit our review below to outdoor systems.

2.1 Novel Outdoor Navigation Technologies

Spatial audio has been used in navigation systems, wherein the directionality of sound indicates the relative location of a landmark or point of interest (POI). Paneels et al. describe a system that uses spatial audio to convey information about POIs in the user's vicinity [41]. Gleason et al. extend this design to find that rich textual descriptions of POIs can augment spatial audio to enhance the discovery process [21].

Other technologies assist with obstacle detection through the provision of audio and tactile cues (e.g.[3, 17, 31, 36]). This includes attempts at augmenting low-tech navigation aids, especially the white cane. The SmartCane prototype uses force feedback to provide feedback about directions and covered movements [12]. The TalkingCane reads RFID chips embedded in Braille markings at locations like building entrances to provide accurate directions to its users [30]. There have also been attempts at crowdsourcing metainformation about sidewalks, including details about missing curb cuts and obstacles [12, 21], and information about landmarks around bus stops [25].

Finally, research has also attempted to find ways to improve navigation technologies that depend on inaccurate localization systems like GPS. Saha et al.'s Landmark AI prototype explored the feasibility of using smartphone-based computer vision to guide visually impaired users across the last few meters to their final destination [42].

There have been many commonly available (i.e., non-research) navigation systems for people with visual impairments including tools that provide turn-by-turn directions (e.g., Google Maps [22]), information about landmarks and POIs in the immediate vicinity (e.g., BlindSquare [10], Microsoft Soundscape [37]), or both (e.g., Nearby Explorer [38]). Visual interpreter tools, which enable users to get sighted assistance from volunteers (Be My Eyes [8]) or professionally trained agents (Aira [4]), have also become popular recently. Our study makes two contributions to the body of work examining the use of outdoor navigation technologies by people with visual impairments. First, we highlight how despite changes in the technology landscape (e.g. since studies like [53]), people's preferences for certain navigation technologies have remained the same, and we provide reasons as to why this is the case. In the process, we also re-validate some of the findings from prior work like [53] which suggests that people with visual impairments use a combination of technologies, both assistive and mainstream, to get around. Second, we also bring to light how newer technologies like visual interpreter tools (AIRA [4] and Be My Eyes [8]) are used to assist with navigation, which has so far not been understood in navigation-related research in HCI and Accessibility.

2.2 Understanding Navigation Practices

Kane et al. found that people with visual impairments use their phones for navigation and encounter challenges like listening to instructions in crowded environments [29]. Kacorri et al. analyzed quantitative data from iMove, a navigation application for people with visual impairments and found that its users often employ iMove in short bursts to inquire about their current location and surrounding points of interests [26]. Abdolrahmani et al. found that people with visual impairments are accepting of errors on their navigation device, though this acceptance is highly contextual [2]. For instance, users were more forgiving when technology did not identify a door in front of them but were less forgiving of being guided to the wrong bathroom door. Zhao et al. investigated how people with low vision navigate surface changes and found they relied on their white cane to inform them of depth changes and not on any other technology [57]. Williams et al. compared sighted and blind navigation and found that both groups understand navigation differently, leading sighted people to struggle in guiding blind companions [52]. In subsequent work, Williams et al. studied O&M experiences, mobility aid preferences, and navigation contexts, concluding that guide dog and white cane users navigate differently, thus suggesting that navigation technologies need to account for both travelling styles [53]. Williams also found that people with visual impairments 1) use technology to complement their existing O&M skills and 2) use a combination of mainstream and assistive technologies to get around [53], findings which we replicate as part of our study. This represents a critical update given the large change in the technological landscape since the publication of the Williams et al.'s study. In addition, we also extend the Williams et al. study [53] by diving deep into the concept of complementarity by discussing the relationship to route preparation and mental mapping, context, navigation aids, simultaneous app use, alternate devices, and visual interpreter tools, all of which have not been discussed in prior work. We also explore contradictory scenarios where information from a technology conflicts with information gleaned from O&M skills/other technologies, which are less discussed in navigation literature in HCI.

3 Methods

We conducted a two-part qualitative study consisting of interviews followed by a diary study. Twenty-three people participated in the interviews (12 female; 16 totally blind, 7 legally blind), ten of whom participated in the diary study. All our participants reported using low-tech navigation aids (Table 1). All participants reported using a white cane, while seven also use guide dogs. Note that when we use the term "people with visual impairments" in this work we are specifically referring to people who rely on navigation aids (i.e., 2-8% of legally blind people use white canes; 2% use guide dogs [9]). We recruited participants via three channels: a listserv for people with visual impairments at a large technology company; solicitations at the annual American Council for the Blind and National Federation for the Blind conferences; and through an

			Navigation Aides			Mainstream Technologies								Assistive Technologies										
ID	Gen.	Age	White Cane	Human Assistance	Guide Dog	Google Maps	Video calls	Siri	Apple Maps	Phone calls	AroundMe	FourSquare	Yelp	Soundscape	BlindSquare	Aira	Dedicated GPS Device	Nearby Explorer	Be My Eyes	SeeingAI	Loadstone GPS	Seeing Assistant Move	Seeing Eye GPS	TapTapSee
P1	F	27	x	x		x	x												x					x
P2	M	25	x	x		x		x	x					x	x				x					
P3	M	46	x	x										x	x	x								
P4	F	47	x	x		x			x						x	x	x							
P5	M	53	x				x				x			x	x	x		x		x				
P6	F	57	x		x	x			x						x	x								
P7*	M	25	x	x		x			x			x	x	x						x				
P8	F	55	x	x	x	x	x							x		x	x	x						
P9*	M	43	x	x		x	x	x		x				x										
P10	F	27	x			x								x	x	x		x	x					
P11*	M	27	x					x																
P12	M	64	x	x				x													x		x	
P13	F	50	x			x	x											x						
P14	F	31			x	x	x											x		x				
P15	F	56	x	x	x	x								x	x									
P16	M	30	x			x								x										
P17*	F	36	x	x	x	x	x		x	x				x										
P18	F	53	x		x	x								x			x							
P19	F	48	x	x	x	x				x				x			x		x			x		
P20*	M	36	x	x		x				x														
P21	M	34	x			x	x	x		x				x	x	x								
P22*	F	70	x					x																
P23*	M	40	x	x		x		x									x							

Table 1. Participant Demographics and Status Quo Technology Use. All participants were totally blind apart from seven legally blind participants marked with an asterisk (*). All participants were iPhone users except P1, who uses an Android phone.

external organization that facilitates accessibility research. This project was approved by our institution's IRB.

We used semi-structured interviews to elicit narrative accounts of people's use of technologies to get around (Supplementary Materials). Interviews were a combination of face-to-face (n=4) and phone conversations (n=19) and lasted between 35 and 60 minutes. All interviews were recorded and transcribed. In the interviews, we asked people about the different technologies they used to get around, circumstances that prompted their use, challenges they encountered, and how they worked around the challenges. Further, we asked about how these technologies fit into their existing navigation practices and specifically, how they interacted with low-tech aids like white canes and guide dogs. We compensated participants $50 USD.

Ten participants from the interview study were invited to participate in a weeklong diary study. Participants were chosen based on the frequency of travel indicated as part of the demographic section of the interview study, focusing on participants who indicated that they frequently took trips outside of their homes. Participants received an email at 4 p.m. daily and had to respond by 9 a.m. the next day. The diary entries comprised five questions (Supplementary Materials) that included locations navigated to, apps and technologies used for travel, features used in apps, and challenges encountered when navigating. We received 65 diary study entries in total. We compensated these participants an additional $25 USD.

The first author conducted all interviews and analyzed the data from the interviews and diary study through an inductive, two phase process. Each phase in turn included one round of open coding [44] and clustering related codes into higher level themes through an axial coding process [44]. In the first phase, 23 codes were developed which were then clustered under 4 themes (orientation tools, turn-by-turn tools, visual interpreter tools, and phone use on-the-go). In the second phase, 14 of the 23 codes from phase one were maintained while 6 new codes were developed for a total of 20 codes (Supplementary Materials). Ten codes in phase two, which included the 6 new codes, were recategorized into four higher-level themes, which were the same as Phase 1. For instance, white cane use, guide dog use, battery concerns, and phone affordances were codes under the *phone use on-the-go* theme. The remaining 10 codes remained uncategorized and included codes that captured navigation-related activities like route preparation and route validation. During the process of data collection, the first author conducted weekly reviews with the remaining members of the research team to go over findings and emergent themes. The first author's unique perspective stemming from interactions with participants and subsequent closeness to the data, made seeking agreement (via multiple coders quantified through measures like Cohen's Kappa) a less suitable means of establishing reliability [35]. In addition to this qualitative analysis, we gathered some quantitative data from the diary study. In order to do so, we classified our participants' diary study entries to understand if they had references to: 1) the use of navigation related technologies (Y/N) and if so, which technologies were used (e.g. Google Maps, AIRA); 2) the use of multiple technologies on the same journey (Y/N); 3) challenges encountered during a journey (Y/N) and the nature of these challenges (e.g. last 100 meters, inaccessible interfaces); and 4) the use of technologies for route preparation and transit related information (Y/N). These were in addition to details about locations people travelled to (e.g. home, work) and the frequency with which they travelled to these locations.

4 Findings

4.1 Technology Classes

Navigation technologies that our participants reported using included smartphone apps (both mainstream and assistive tech) and dedicated GPS devices. Many of the tools provide turn-by-turn directions such as Google Maps [22] and Apple Maps [5] , though others were orientation tools used to get information about one's vicinity including Microsoft Soundscape [37], AroundMe [6], and BlindSquare [10]. Siri, Apple's voice agent, was also used to acquire orientation details. Several tools provided both turn-by-turn and orientation details including dedicated GPS devices [49, 50], Nearby Explorer [38], Seeing Assistant Move [46], Seeing Eye GPS [47] and Loadstone GPS [32]. Visual interpreter tools used included Aira [4], Be My Eyes [8], and video calls (e.g., Facetime) with friends and family. Less commonly used tools that did not fit into these three categories were phone calls, business directory services used to find business details and addresses (Yelp [56] and Foursquare [19]) and object identification apps to identify signs (Seeing AI [45] and TapTapSee [48]).

Often, technologies were used in combination and at different times to complete a journey. We highlight how navigation technologies were used in conjunction with each other and with participants' navigation aids pre-journey, on-journey, and post-journey.

4.2 Pre-journey

4.2.1 Complementarity in route preparation and mental mapping

Outdoor navigation for our participants began well before the journey. All participants engaged in two pre-journey activities: getting an overall sense of the route to a destination and determining the best mode of transit to get there. A few participants (n=3) also described a third activity: choosing which tool to use on-journey. Some participants highlighted the importance of getting a route overview:

> You have a good mental map and you're more confident than you otherwise would be… you know where you're going and what the address is, and you also understand how [anonymized city] is laid out – P2

Like P2, others highlighted how getting an overall sense of their route and surroundings helped form a mental map, findings which have been reported by Kacorri et al. in their quantitative analysis of iMove, a navigation application for people with visual impairments [26] and leveraged by Guerreiro et al. to design technologies to better enable virtual walkthroughs of specific routes [23]. In addition to validating these previous findings, our qualitative data provided a novel understanding of the value of the route preparation process – it made journeys quicker, more direct, and less error-prone (a key step in O&M training [33]). Furthermore, participants, like P2, felt that using an app to build a strong mental map *before* their journey made them more confident and better prepared them for scenarios in which technology failed them *during* their journey: they could use their mental map to retrace their steps and recount details like street names or intersections. Finally, it is clear mental mapping reduces phone use and interactions on the go, which is significant for people with visual impairments who find it particularly difficult to do so [1] and who have battery concerns resulting from phone over-use for navigation. Consequently, a majority of our participants (n=15) used mainstream turn-by-turn technologies like Google Maps to learn routes and improve their mental map by previewing suggested routes which helped them reduce phone use while actually navigating.

> I find it easier to check Google Maps ahead of time to kind of map out my [path]... we do an initial understanding of what streets we're gonna cross, where we're gonna go, how long it's gonna take to get there, how difficult the trip is going to be, to get an understanding... it's almost used as a security when we're there… - P13

In addition, our participants particularly valued the integration of public transportation (e.g., bus schedules) with walking directions in Google and Apple Maps. Azenkot et al. elucidated some of the challenges that people with visual impairments face in planning for trips with public transit because local transit websites are often inaccessible to screen readers [7]. Here we see that the Google and Apple Maps interfaces were relatively accessible for reading suggested travel routes and transit details and therefore allowed participants to easily compare and switch between multiple ways to get to a destination (e.g., walking vs. public transit vs. ridesharing). Although work by Williams et al. [53] suggested that people with visual impairments use mainstream apps like Google Maps to get around, it stopped short of examining the specific ways they are used, especially in the route preparation process. The ability to compare different transit options (including transit time, cost, etc.) to decide which is best for the participant at a given time was one of the major reasons for their use pre-journey. The importance of mainstream apps to route preparation was further visible in our diary study where 8 out of 10 participants reported using these Google and Apple maps at least once to search for addresses, look for transit options/details and compare routes (in all, 19 out of 65 entries had references to route preparation activities). This was despite the diary study questions focusing on on-journey technology use.

> Timing transit is really important to me... When I use [Google Maps], I use it to plan out my route getting there, especially when it comes to public transit, and what, based on my knowledge of the traffic, etc., around where I am, I use it to sort of pick my best option for routes - P20

Google Maps was the most popular mainstream turn-by-turn app to assist with route preparation, although some (n=6) reported using other apps like Apple Maps. Data accuracy was a major factor impacting app preferences. Participants referred to the accuracy of different data points on the apps including distance information, travel time, and transit arrival and departure times. A few also noted how UI accessibility and intuitiveness influenced app choice.

> As I said earlier, I would pick Google Maps over Apple Maps because it has more features, it has more directional accuracy as far as guiding somebody telling them different turns and stuff... – P17

The accuracy of transit timing information provided by navigation apps (e.g., arrival and departure times) was particularly important. Several participants indicated that Google Maps often accurately accounted for schedule changes and delays while Apple Maps only presented static information. This was perceived as a critical difference in accuracy that resulted in transit users opting to use Google Maps. Furthermore, some participants felt that addresses and related updates (e.g., changed bus stop locations or road closures) were more likely to be available on Google Maps than other apps – another key reason for its preference by our participants.

Our participants' preference for mainstream apps like Google Maps in the route preparation process was despite some remarking that these apps were not designed while keeping people with visual impairments in mind. Although the apps were good for providing a general sense of the route to a destination, other details relevant to participants, particularly for walking details (e.g., landmarks and obstacles they would encounter *en route*, layout of streets in relation to each other,) were unavailable. In contrast, these details are often available on apps that are designed specifically for people with visual impairments like Nearby Explorer. Furthermore, others noted how the recommended routes were always the shortest (by distance or time) rather than the most accessible route:

> It's pretty accessible in terms of selecting the mode of transit... it's not completely designed, keeping someone visually impaired traveling independently in mind... It just tries to show you the shortest route...the shorter route might not necessarily be the most accessible… When a sighted person looks at Google Maps they can actually see popular things... and orient themselves... when I look at directions on Google Maps the textual directions… they would only contain landmarks from where I have to turn. – P1

This indicates that while picking between different transit options to a destination was easy enough, choosing walking routes based on access preferences was difficult due to the pertinent information being largely represented visually. Despite these failings, the integration of transit and walking in routes, the perceived accuracy and certainty over the availability of different data points, and the relative accessibility of the tool caused nearly all of our participants to still use mainstream turn-by-turn tools like Google Maps to seek information before beginning a journey.

4.3 On-journey

Our participants' diary entries indicated that technology was an integral part of their everyday travels, especially if they were by themselves (58 of 65 entries had accounts of tech use for travel). Moreover, 8 of 10 diary study participants reported using mobile technologies on-journey even to locations they visited frequently like home and work.

4.3.1 Complementarity and context

Participants used different tools to suit different contexts. For instance, turn-by-turn directions were particularly useful to track progress while on mass transit or ride-sharing services, as highlighted by prior work [13, 27, 28, 40]. Given that both Uber and Lyft use Google Maps to route drivers, participants could follow the route the driver was taking by accessing Google Maps on their own phones. This made P1 and P5 feel safer by allowing them to confirm that the driver was on the right route to the destination. The different affordances of tools also meant that participants found different tools useful for different phases of the same journey. For instance:

> I typically will use Google Maps if I am trying to find out where a place is or how close it is to me… And then I use Nearby Explorer probably when I'm walking, or… in a vehicle… traveling by a car, to know where I'm at..., if we're on the right track getting there, that sort of thing. – P14

Williams et al. suggest that people with visual impairments use a combination of apps to get around [53]. We found that this was the case with our participants as well and what's more, was relatively common even for travel to everyday locations like home and work. Our diary study pointed to 19 instances (out of a total of 65) where at least 9 out of 10 participants used multiple technologies on the same journey. While many found mainstream apps like Google and Apple maps ideal for route preparation (as previously highlighted), others like P14 found that such apps were inadequate for use *en route*, especially when one sought details and confirmatory messages about their current location. Many participants (n=18) resorted to using tools like Nearby Explorer, Microsoft Soundscape, Blind Square, or AroundMe during the journey to fill in for these inadequacies. While Nearby Explorer announced POIs and landmarks, including the ones participants had marked, Microsoft Soundscape additionally offered a spatialized "audio beacon" oriented in the direction of the user's destination. Announcements about landmarks and POIs along familiar routes allowed participants to compare real-time information with their mental map of the route and to add to their mental map.

> Most of what I was doing was more in the way of exploring than navigating— finding out new things about areas I travel through regularly and adding to my over-all orientation in those areas… I was building up a picture of the areas I was traveling through. – P8 (Day 2, Diary entry)

4.3.2 Complementarity and navigation aids

Not only did technologies complement each other through their different affordances (e.g., Nearby Explorer filling in for Google Maps' deficiencies *en route*), but they also complemented our participants' use of navigation aids, such as the white cane or guide dog. Verbal instructions (e.g., turn-by-turn directions) and announcements complemented information participants obtained from the white cane, guide dog, and their surroundings to help participants navigate to their destination. Irrespective of the choice of app or tool participants used on-the-go, they were only willing to use technology to the extent that it complemented their use of a white cane and/or guide dog. As P2 explains:

> Apps essentially augment that experience. They supplement the experience of the white cane, the white cane is really out there to give you a lot of sensory information in terms of what is around you, what is in front of you, for obstacle detection... These apps are more of like navigation directions, so they kind of complement each other. – P2

The complementarity in this case resulted from the difference in the nature of information P2 was obtaining - verbal instructions from apps and sensory information about what was ahead of him from the white cane, which he pieced together in order to assist him with his walking. On the other hand, he expressed his distaste for computer vision-based tools that assisted with obstacle detection, primarily because he felt that such tools did not complement his use of the cane but overlapped with the information it was providing.

Participants with guide dogs noted how the apps complemented their use of guide dogs *en route*. For instance, P8 noted:

> They usually pretty much agree, but then the dog is not telling me where the Starbucks is... it's different kind of information. They tend to agree once I get there... The app has said that there's a Starbucks there in the door, the dog says here's the door and lo and behold it's the Starbucks. It's usually right. – P8

In this case, the information from the app was insufficient for P8 to determine the location of the door, something that her dog was trained to recognize and assist with, especially in the case of frequented locations. Likewise, dogs also assist with finding ways around obstacles, something that mainstream apps do not afford.

Nearly half of our participants (n=10) reported carrying their phone in their unoccupied hand while on-the-go while the rest of our participants put their phone away in other locations (e.g., a bag, pocket, or lanyard around their neck). Both strategies entailed trade-offs.

> I have my cane in my right hand... and then my phone in my left and basically I'm just listening to the directions… I get the look of why is this guy blind and he's looking at his phone? Is he texting? That type of look… There's a couple of times that you just want to walk and you want to concentrate and the app's kind of you have to look down or listen to it and you're like, "Why, do I need to do that?" – P7

Here, P7 did not wear earphones to listen to directions, instead playing them on his phone's speaker. This strategy allowed him to pay attention to his surroundings and to directions from the app on his phone without the former getting in the way of the latter, though it raised concerns over the social perceptions of him as he interacted with his phone in a public space.

Most participants used earphones (n=15) to listen to audio output from their devices and felt that it got in the way of cues they were receiving from the environment. Some worked around this by using an earphone on one ear (so that they were able to pay attention to both at the same time) or by using bone-conduction headsets (n=4). Although findings from previous studies [1] suggest that people with visual impairments adopt one strategy of attending to environmental cues and app audio i.e., by using a single earphone, we found that participants who did so were in the minority. Many participants used other strategies like using the phones speaker (in lieu of earphones altogether) or using earphones on both ears, despite the trade-offs entailed therein.

Verbal directions from apps made it possible for our participants to navigate without necessarily having to interact with their phones during their journey. However, despite all apps affording minimal interactions *en route*, nearly all our participants reported having faced circumstances where they had to interact with their phones on-the-go including: needing to repeat instructions and announcements, troubleshooting apps and phones when something went wrong, and switching between navigation apps when one stopped working or proved to be insufficient for their needs. However, interacting with the phone when on trips was perceived to be cumbersome and slowed participants down as it was impossible for them to walk and interact with the phone at the same time. Subsequently, they needed to stop and find a safe location out of the way on the side of the street before pulling out their phone to interact with it, as previously noted by Abdolrahmani et al. [1]. However, despite the desire of participants to reduce phone use on the go, we found that switching between navigation apps was common *en route*. This typically happened when participants felt that one app was not giving them the right information or when one stopped working altogether. In both these cases, they complemented this app with another, thus filling in for the gap created by the deficiencies of the first app.

Although our participants found interacting with touch-screens cumbersome, they perceived some alternate interactions much more positively. For instance, some of our participants (n=7) reported using Siri (Apple's voice assistant) to seek orientation information on-the-go, which has been suggested by prior work [1, 14]. They found it more convenient to pull out their phones (or interact directly with their Bluetooth earphones) and summon Siri via a hardware button, as compared to the challenge of interacting with touch screens. By pressing and holding the hardware button, participants could say "where am I" to which Siri typically responds by reading out an address. Furthermore, many of our participants were concerned about battery use; for them, Siri offered a more battery-friendly way of determining where they were than GPS apps.

> There's a lot of times I'll just ask Siri… "Where am I?" And she'll… give me an address where I'm at... Just fast and easy... Don't have to load anything, it's just if you have data, it's available. - P12

Abdolrahmani et al. [1] described this appropriation of Siri by visually impaired users, however, our findings also add nuance to the this observation. We found that while using Siri was quick and convenient, its use had tradeoffs which affected its utility for certain use cases. For instance, participants like P12 noted that in response to the question "Where am I," Siri often responded with an address rather than the name of a POI or landmark, thus requiring interpretation by the end user to figure out where they were. Some also observed that this information was not always accurate, which was problematic.

Others spoke of the advantages of vibrotactile feedback that some apps provided, which often complemented the verbal instructions in apps like turn-by-turn tools, such as vibration feedback just before turns. This feedback served as a convenient reminder and allowed users to keep the phone put away.

Many participants expressed concerns over GPS apps draining their battery and moderated their use of tech to minimize battery use. For some participants like P13, this meant memorizing the step-by-step directions from the route preparation phase and for others like P18 this entailed storing step-by-step directions in an offline tool or other non-phone devices (like Braille readers).

> So, we used Google Maps to kind of give us… a general understanding of where we're going… so sometimes we save those directions or we write them down… (and on-the-go) there was a time that I used it that my phone had died because Nearby Explorer just...so, I have to remember... to not leave it running in the background to make sure that I turn it off quickly. Use it for what I need… but when I know that I'm on the right path, I turn it off quickly. – P13

When P13 did not save or write down the directions, she also described how she minimizes GPS app use by ensuring that she uses the apps intermittently rather than continuously. This necessitates that one remember to constantly turn on and quit apps and moreover, in the case of P13, pull the phone out from where she put it away (her bag) before using it, which slows people down. Nonetheless these steps are indicative of the work that the likes of our participants are willing to put in in order to reduce battery usage on-the-go.

4.3.3 Complementarity through simultaneous app use

Many participants (n=14) noted that they only used one navigation app at a time although they switched between apps in the case that one failed or proved inadequate for their navigational needs. It is clear from our above findings that some apps lend themselves to complementary use at the same time due to their different affordances and information they provide (e.g., turn-by-turn directions from Google Maps or

Nearby Explorer combined with orientation information from Soundscape via directional audio beacons). Prior work suggests that using apps at the same time could be cognitively demanding for people with visual impairments and while we found this to largely be the case, we also found that a few participants did in fact leverage this complementarity to use apps at the same time.

> I was sitting on the bus and trying to figure out what stop I was at. I decided since Nearby Explorer and Soundscape both will tell you what you're passing, I tried running them at the same time. That was kind of amusing because every once in a while they would speak at the same time. Often one would hit a location that the other one didn't... I wasn't quite sure who to believe... – P6

Here, we see that P6 benefited from the different announcements by Nearby Explorer and Soundscape, although she was uncertain about which information to trust. Note that P6 was on a bus when using both apps as opposed to walking where she would need to be more receptive to her surroundings, make decisions about where to go, and receive and give instructions to her guide dog. On the other hand, participants who explicitly stated that they avoided using multiple apps at the same time, especially while walking, did so as they believed receiving multiple instructions at once would be distracting and interfere with navigating. For others, concerns about GPS apps draining their phone’s battery was a reason to avoid simultaneous app usage.

4.3.4 Complementarity through alternate devices

Some users of dedicated GPS devices like Trekker Breeze noted how these devices complemented their use of the phone, saving battery and data bandwidth by ensuring that they did not use their phone on-the-go.

> My main thing with having a separate GPS, is it's not using my phone data, and it's not draining my phone battery… So that's the biggest plus of it. But if I need to use my phone, it's fully charged and it's enough for me to use… When you're using the GPS app, it can go through the battery fairly quickly… And I don't want to be stuck somewhere, and then try to return home and my battery is dead – P18

Although using these devices required that they are charged in the first place (a necessary pre-journey activity) and carrying an additional device (entailing additional physical effort), participants noted that this was a worthwhile trade-off, as they could now use their phones only in the case of emergencies (like when the dedicated GPS devices did not work or stopped working). Here, we see that it is not just apps that complement each other, but different devices, as well.

4.3.5 Complementarity through visual interpreter tools

No tool that relied on GPS was precise enough to guide participants to their exact destination. Participants noted this particularly in the case of mainstream turn-by-turn tools, where instructions like "You have arrived, and your destination is on the right" were never quite sufficient to determine the entrance to the location they meant to enter. Although those with guide dogs visiting familiar locations relied on their dogs to find entrances, it was problematic when they were travelling to new locations. Our diary study also indicated that issues within the last few meters to a destination were commonly encountered by participants on everyday travels. Five out of 10 participants, reported instances where their GPS-based tools failed to give them precise enough directions to reach their destination at least once (i.e., a total of 9 of 24 entries, which pointed to challenges experienced on everyday travels).

A popular means to address this last-few-meters challenge was the use of visual interpreter tools. While some of our participants used Aira (n=7), a few (n=4) also used Be My Eyes. While Be My Eyes volunteers got access to the participants’ visual field through their phones, Aira worked via either the phone’s camera or a pair of specialized glasses that participants had to put on before connecting to the smartphone app. Nearly all Aira users in our sample reported using the service with the glasses, with some noting that they enabled Aira agents to get full access to their visual field, which was difficult with the phone. By connecting to either service on their phones, participants placed calls, described their needs, and got assistance.

> Usually the navigation apps are 15, 20 feet off from the actual destination. If you're looking for the door handle or where the actual door handle is, if the business is pretty quiet… then Aira can be helpful. If you need to locate the front the desk or whatever, it helps with that.– P21

By connecting to volunteers or trained agents, visual interpreter tools addressed the last-few-meters gap of GPS technologies. In addition, visual interpreter tools also proved useful in other circumstances, including when participants were lost and when the need for assistance was immediate.

> I also use Aira sometimes if I'm in a strange place, I'm not quite sure even what to tell the dog. I'll call Aira up and see if we can look around with eyeballs and tell me where the place I'm looking for is… when I was in [anonymized city, a new location], we were looking for a certain restaurant. We called them when we were about a block away and asked if they could see it. Sometimes there's just no replacement for a pair of eyes...– P6

While resorting to human assistance from people around was an option for a few, this entails a process of determining if people are around, approaching these people, describing one's needs, and then getting assistance which does not always result in the right kind of help. On the other hand, with Aira, participants felt a degree of certainty that professionally trained agents who have access to the participant's location and visual field can provide the right kind of assistance. The usefulness of Aira for short, immediate tasks was highlighted when two diary study participants described instances when Aira complemented turn-by-turn directions and filled in for their lack of precision by confirming they were at the right bus stop. Our diary study indicated only three instances of Aira use for navigation by two participants, suggesting that these tools were less useful for everyday travels to frequented locations. However, from our interviews it was clear that that participants saw a great deal of value in both Aira and Be My Eyes for the above-mentioned reasons.

However, using either of these visual interpreter tools was not without its challenges. Aira is a paid service and many participants described how they limited the use of Aira because of its high cost. On the other hand, Be My Eyes, although free, connects people with visual impairments to volunteers and some participants noted how these volunteers, while able to assist with certain tasks, could not be asked to assist with navigation tasks because they were not reliable and able to provide precise instructions, which could in turn challenge their personal safety (thus they used them for other tasks in safe spaces like homes or to read signs, etc.).

> Yeah the price [is a challenge with Aira]. Overall though, the service is fantastic… you're getting someone who's professionally trained at Aira... Especially for travel, I think Aira is definitely a notch above Be My Eyes… they know exactly how to talk with you about how to... they just know how to do it and do it well and they're very efficient at it... I've used them [Be My Eyes volunteers] for things, like to check something on a screen or things like that where it's not as important… I have a much greater level of confidence with Aira in a traveling type of situation due to the amount of training that they receive - P10

Switching to Aira and Be My Eyes also entailed a great deal of work for our participants. A few Aira users noted the physical effort in carrying the glasses; there is work involved in finding these glasses, putting the glasses on, and connecting them to the phone. On the other hand, with Be My Eyes (and phone-only Aira users) there was time involved in pointing the phone's camera in the right direction to allow assistants to access their visual field. Needless to say, these tasks (especially pointing the phone in the right direction) are further complicated by participants having their white cane or guide dog in one of their hands.

4.3.6 Contradictory Scenarios

As we noted earlier, many participants use multiple apps to get around and encountered situations where they had to switch between them on-journey especially when they sought to validate the information from one app, when they were uncertain about the information they were receiving from another, or when they sought a different kind of information (as in the case of visual interpreter tools). In both cases, while most apps complemented each other, a few participants reported experiences where apps contradicted each other, giving them different information and leaving them confused and disoriented.

> I made a lot of turns in a part of my home area that is mostly residential and just got to where it was like, okay, did I miss the turn... I tried to figure out what intersection I was actually at, and I think I tried three different [apps] and they all thought something different… I think I got down to where two of them agreed and I thought good enough and kind of went with that theory. But because I was getting such pretty drastically different results, it became almost worse than not knowing... It doesn't happen often, but when it does, it seems to be, like I said a bit disorienting because I started to question my own will, did I turn?. – P8

P8 was uncertain about the information she was receiving from one app and switched to confirm the information and when the data did not agree, used a third app to validate information from the first two apps. When the data from the apps did not agree, not only was she forced to determine which information was right, but it also left her questioning steps she had undertaken previously. Although P8 handled this by trusting the two apps that agreed, others reported resolving uncertainty by doing away with apps altogether and falling back on their O&M skills (listening to sounds, asking for assistance).

Likewise, working with dogs and tech simultaneously also had challenges. Some participants noted how the timing of turn-by-turn instructions was often too delayed (preferring to receive instructions well ahead of time) and did not take into account the time required for participants to pass on instructions to the dog. This left them disoriented, as the dog had already guided them along a certain direction before the announcement pointed them in the same direction. A few guide dog users (n=3) noted instances when disagreement could occur between their guide dogs and apps.

> It was awkward because sometimes I would override him because the app would say you have to turn left here. There was no left there. Maybe the left turn was 50 feet up, or maybe it was 50 feet back, or whatever. It sure wasn't anywhere near where we were walking. He [my dog] would get frustrated, of course, because he didn't know that I was hearing some app... generally, if there's too much information and what the dog is telling me is not matching that information, or if I really need to give him more attention and listen less, then I'll pause the app.. I've gotta trust the dog. That's what he was trained to do.– P6

Here, we see that the incorrect timing of instructions resulted in P6 asking her dog to turn left, when in fact there was no turn ahead of her, frustrating her dog. Like P6, all participants reported on trusting their dog rather than the app as they believed the dog was trained to assist with O&M and was consequently far more reliable.

4.4 Post-journey

Some participants (n=6) reported saving favorite locations upon completing a journey in Google Maps or Microsoft Soundscape. This process of favoriting a location ensured convenient access for repeat journeys. In addition to favoriting locations, participants also added markers to capture details missing from apps, such as P15's driveway:

> … what I did with Soundscape… there are two driveways to my apartment, and he [my guide dog] chooses to go in the first driveway and we use the second driveway. So I have marked the second driveway as a favorite and a little tone goes off when we get to the second driveway.- P15

Markers could also be customized to announce POIs and landmarks that could assist with orientation during walking journeys. Participants noted how the accessibility of marking interfaces played a key role in allowing them to capture these details. For instance, in Google Maps one has to zoom into a map and sometimes also pan to drop a pin; this process was difficult to achieve without sighted help (P14 recalled an instance where she had dropped a pin on a wrong location, which she realized only after someone sighted told her). On the other hand, this process was much more accessible in assistive tools like Nearby Explorer, where one can set a marker by a cursor through the use of arrow keys in the app.

5 Discussion

In this section, we discuss some of the design implications that result from our findings and highlight how 1) complementarity can be enhanced by taking into consideration the multiple dimensions of accuracy and navigation aids (like guide dogs) while designing navigation apps, and 2) how the accessibility of mainstream navigation apps like Google Maps and voice agents like Siri might be improved through novel features. In doing so, we also discuss how these design implications could enhance the navigation experiences of people with visual impairments.

5.1 On complementarity

Through an analysis of 23 blind participants' experiences using common navigation technologies in their day-to-day lives, we revealed how people with visual impairments use a combination of technologies to get around. We validated a key finding from Williams et al. and find that technology is only useful to the extent that it complements people's O&M skills [53], by assisting with mental mapping, route preparation and working in conjunction with mobility aids. In addition, our study extends upon the Williams et al. study in two key ways. First, we provide a deep exploration of what complementarity means in practice, finding that complementarity is often the result of the difference in modalities of information conveyed to participants (e.g., tactile information from white cane + audio information from apps, vibrotactile feedback from apps + audio information). Second, we find that complementarity not only extends to the relationship between apps and mobility aids but also to the relationship between various apps the user operates, meaning that information from different forms of technology was often pieced together to get a complete picture (e.g., turn by turn directions + information from visual interpreter tools, GPS devices complementing phones). In doing so, we also uncover how participants use relatively newer tools like Aira and Be My Eyes to get around. Next, we discuss how design might assist in enhancing this complementarity.

Our participants often sought information prior to the start of the journey to develop a mental map and to assess the difficulty of a given route. Here, the perceived accuracy of mainstream tools like Google and Apple Maps, including their many dimensions (availability of latest information, transit timings, etc.), resulted in participants using them for the above-mentioned navigation tasks and use during the journey as well. Prior work has attempted to draw up personality characteristics (e.g., exploration attitude and technology reliance) and scenario characteristics (e.g., terrain, crowd density, and transportation availability) of people with visual impairments, as a part of a persona creation process intended to assist designers with the creation of user friendly navigation tools [53]. Given our findings, "accuracy" should be considered as a key addition to the scenario list, extending the already present "GPS availability" characteristic; this notion of accuracy includes many dimensions (e.g., distance, time, and transit related information). This is important as the perception of accuracy of mainstream and assistive technologies was key to our participants using them in the first place. Furthermore, in addition to the multiple dimensions to accuracy, other findings in this study such as participants' use of newer technologies like AIRA, Be My Eyes, and voice interactions highlight the need to update personas characterized in [53], and we believe that this is a valuable direction for future work.

Although participants generally believed mainstream tools like Google Maps and Apple Maps to be accurate, they noted that information on these tools was occasionally out of date or inaccurate, forcing them to determine alternative paths *en route* when encountering unexpected obstacles. Providing information about obstacles, detours, and other things that could impact one's trip pre-journey would be extremely valuable, especially for pedestrians. Prior research has discussed how information that could provide vital cues about sidewalk accessibility including the presence of curb cuts and obstacles [24, 43] can help people with mobility impairments, and our study suggests that people with visual impairments would value such information as well. Specifically, this information could assist people when deciding which route to take in the pre-journey phase, in addition to reducing cumbersome within-journey phone interactions. Of course, it should be noted that participants' desire to front-load more general information (e.g., crossings, street names, etc.) prior to starting a journey may also be because it is so difficult to safely access this information while *en route* without impeding their O&M skills. If such information were easily accessible during a journey, it could be very helpful in easing the cognitive load of travel. Participants also faced issues with inaccuracy of apps and technology during the journey. To ameliorate the challenges this poses for users, technologies should acknowledge potential inaccuracies whenever possible (e.g., map applications notifying the user when GPS accuracy is measurably poor) and communicate this state to users in an accessible fashion. This acknowledgement of inaccuracies and errors when possible could make the decision to seek recourse by switching apps or technologies more straightforward and thereby improve the navigation experiences of people with visual impairments.

Like Williams et al., we also noted that white cane and guide dog users had different navigation styles and requirements [53], and prior work by Ohn-bar et al. has attempted to take personal navigation styles as an important consideration for their navigation app [39]. While the study by Ohn-bar et al. takes into consideration characteristics like walking speeds and reaction times [39], it does not take into consideration the use of mobility aids like guide dogs which our participants occasionally had trouble using technology with. In our work, problematic scenarios arose when people with guide dogs did not have sufficient time between when they received an instruction and when they acted on it due to the time requisite in giving instructions to the dog. Future systems should reduce these scenarios and complement the various navigation styles of people with visual impairments by allowing a user to specify their primary navigation aid in a profile setting and then adapting their user interface to account for this.

We also saw that switching between applications was prevalent among our participants in cases when one technology stopped working or did not serve their needs. The only good example of a design that eased this burden for our participants was calling an Uber or Lyft in Google Maps. Our participants indicated that this allowed them to quickly look for addresses and locations and call a ride-share (Uber) without leaving the current experience, improving efficiency. However, most of the time, they needed to switch between apps as their need for information changed. Our participants reported it was particularly common to switch from tools providing orientation and turn-by-turn directions to visual interpreter tools over the last few meters. This common switchover could be addressed in a few ways. First, turn-by-turn and orientation tools could simply add a button in to open a visual interpreter services (e.g., a button within Nearby Explorer or Google Maps that would connect to Aira or Be My Eyes). Another approach would be to integrate or link to computer vision tools that could help address common challenges in the last few meters as suggested by Saha et al. [42]. Making switching between apps easier would also reduce the number of interactions *en route*, which is perceived to be cumbersome by people with visual impairments as indicated by both our results and by prior research [1].

5.2 A case for mainstream accessibility

Mainstream non-assistive tools were popular among our participants, particularly Google Maps for pre-journey route preparation primarily because of the integration of walking directions and transit routes and the perceived accuracy of data points like time, distance and transit information. Given the pervasiveness of Google Maps in the smartphone market, it is important to consider how it could be made more accessible and usable to people with vision impairments. Google Maps primarily offers its users a visual interface from which one can glean details about POIs, landmarks, and intersections for given route. Making many of these details available in text, and therefore accessible to screen readers, could assist travelers with better pre-journey preparation such as building mental maps, identifying potential route alternatives, or flagging nearby shops, landmarks and POIs. These details will supplement the detailed verbal directions that Google Maps has recently made available to improve the on-journey navigation experiences of people with visual impairments [51]. Additionally, these details would be particularly helpful for travelers using applications such as Microsoft Soundscape which announces many of these details *en route*, thus confirming one's location and assisting with orientation along familiar routes. Landmark and POI identification could be further supported by an accessible means to add pins and favorites in a manner that does not require visually oriented interactions like panning and zooming on the map itself.

Finally, many participants noted how the inaccessibility of mainstream turn-by-turn tools stemmed partly from ranking routes by distance or time rather than physical accessibility. Prior work in the context of people with mobility impairments has started to address this challenge, through the creation of inclusive routing solutions that take into consideration barriers to access [11].

Concerns over battery use were common among our participants, likely indicative of the frequency of use of GPS apps, and exacerbated by the use of older phones. While sighted people may not turn on mapping apps to navigate to everyday locations like home and work, our participants commonly used these apps anytime they were out and about. It is thus important for designers to be mindful of the extent of the use of navigation apps and to design apps that are optimized for battery use. Furthermore, while it was unclear if participants used these navigation apps on curtain mode i.e. while putting the phone to sleep, it is likely that solutions like DarkReader can reduce battery consumption and contribute to alleviating concerns over battery use [55].

We should also note the potential of voice interactions with embedded voice assistants like Siri, Google Assistant, and Cortana to enable people to ask "Where am I?" without requiring them to consult a mapping app. This would be both convenient and potentially save power. Furthermore, voice agents enable hands-free interaction with a trigger phrase or a single button press on the phone or on a headset, a particular boon when the phone is tucked away. Finally, it would also be helpful if such agents provided a richer context to one's location than simply an address, as Siri currently does. Altering this response to provide a heading, POIs, and landmarks may offer more utility to people with vision impairments.

6 Limitations

Our sample of participants were from the United States of America, used mobility aids (white cane and guide dogs) and some form of technology to assist with navigation. This is likely not representative of the larger population of people with visual impairments within the US or abroad. Additionally, our results are based on a small sample of interviews and a single diary study, meaning that they are not necessarily generalizable to all populations of people with visual impairments.

7 Conclusion

In this paper, we conducted a qualitative inquiry into the use of commonly available navigation apps and technologies by people with visual impairments. We explored the idea of complementarity between navigation technologies to understand how it plays out in the context of modern commonly available navigation technologies and mobility aids. We find that complementarity exists between technologies and is primarily the result of various technologies providing disparate information or conveying information through different modalities. Based on these findings, we provided design recommendations to enhance this complementarity and to improve the overall navigation experience for people with visual impairments.

REFERENCES

[1] Abdolrahmani, A. et al. 2016. An empirical investigation of the situationally-induced impairments experienced by blind mobile device users. *Proceedings of the 13th Web for All Conference* (2016), 1–8.

[2] Abdolrahmani, A. et al. 2017. Embracing Errors: Examining How Context of Use Impacts Blind Individuals' Acceptance of Navigation Aid Errors. *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, 2017), 4158–4169.

[3] Aguerrevere, D. et al. 2004. Portable 3D sound/sonar navigation system for blind individuals. *2nd LACCEI Int. Latin Amer. Caribbean Conf. Eng. Technol. Miami, FL* (2004).

[4] Aira: *https://aira.io*.

[5] Apple Maps: *https://www.apple.com/ios/maps/*.

[6] AroundMe: *www.aroundmeapp.com*.

[7] Azenkot, S. et al. 2011. Enhancing Independence and Safety for Blind and Deaf-blind Public Transit Riders. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (New York, NY, USA, 2011), 3247–3256.

[8] Be My Eyes: *https://www.bemyeyes.com*.
[9] Blindness Statistics: *https://nfb.org/resources/blindness-statistics*.
[10] BlindSquare: *https://www.blindsquare.com*.
[11] Bolten, N. et al. 2017. A pedestrian-centered data approach for equitable access to urban infrastructure environments. *IBM Journal of Research and Development*. 61, 6 (2017), 10–11.
[12] Branig, M. and Engel, C. 2019. SmartCane: An Active Cane to Support Blind People Through Virtual Mobility Training. *Proceedings of the 12th ACM International Conference on PErvasive Technologies Related to Assistive Environments* (New York, NY, USA, 2019), 327–328.
[13] Brewer, R. and Kameswaran, V. 2019. Understanding Trust, Transportation, and Accessibility through Ridesharing. *CHI '19 Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (2019).
[14] Brewer, R.N. and Kameswaran, V. 2018. Understanding the Power of Control in Autonomous Vehicles for People with Vision Impairment. *Proceedings of the 20th International ACM SIGACCESS Conference on Computers and Accessibility* (New York, NY, USA, 2018), 185–197.
[15] Cheraghi, S.A. et al. 2017. GuideBeacon: Beacon-based indoor wayfinding for the blind, visually impaired, and disoriented. *2017 IEEE International Conference on Pervasive Computing and Communications (PerCom)* (2017), 121–130.
[16] Chumkamon, S. et al. 2008. A blind navigation system using RFID for indoor environments. *2008 5th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology* (2008), 765–768.
[17] Dakopoulos, D. and Bourbakis, N.G. 2009. Wearable obstacle avoidance electronic travel aids for blind: a survey. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*. 40, 1 (2009), 25–35.
[18] Erickson, W. et al. 2017. Disability statistics from the American Community Survey (ACS). Ithaca, NY: Cornell University Yang-Tan Institute (YTI).
[19] Foursquare: *www.foursquare.com*.
[20] Ganz, A. et al. 2010. INSIGHT: RFID and Bluetooth enabled automated space for the blind and visually impaired. *2010 Annual International Conference of the IEEE Engineering in Medicine and Biology* (2010), 331–334.
[21] Gleason, C. et al. 2018. FootNotes: Geo-referenced Audio Annotations for Nonvisual Exploration. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 2, 3 (Sep. 2018), 109:1--109:24. DOI:https://doi.org/10.1145/3264919.
[22] Google Maps: *https://maps.google.com*.
[23] Guerreiro, J. et al. 2017. Virtual navigation for blind people: Building sequential representations of the real-world. *Proceedings of the 19th International ACM SIGACCESS Conference on Computers and Accessibility* (2017), 280–289.
[24] Hara, K. et al. 2013. Combining crowdsourcing and google street view to identify street-level accessibility problems. *Proceedings of the SIGCHI conference on human factors in computing systems* (2013), 631–640.
[25] Hara, K. et al. 2015. Improving Public Transit Accessibility for Blind Riders by Crowdsourcing Bus Stop Landmark Locations with Google Street View: An Extended Analysis. *ACM Trans. Access. Comput.* 6, 2 (Mar. 2015), 5:1--5:23. DOI:https://doi.org/10.1145/2717513.
[26] Kacorri, H. et al. 2016. Supporting orientation of people with visual impairment: Analysis of large scale usage data. *Proceedings of the 18th International ACM SIGACCESS Conference on Computers and Accessibility* (2016), 151–159.
[27] Kameswaran, V. et al. 2018. "We Can Go Anywhere": Understanding Independence Through a Case Study of Ride-hailing Use by People with Visual Impairments in Metropolitan India. *Proc. ACM Hum.-Comput. Interact.* 2, CSCW (Nov. 2018), 85:1--85:24. DOI:https://doi.org/10.1145/3274354.
[28] Kameswaran, V. and Hulikal Muralidhar, S. 2019. Cash, Digital Payments and Accessibility: A Case Study from Metropolitan India. *Proc. ACM Hum.-Comput. Interact.* 3, CSCW (Nov. 2019). DOI:https://doi.org/10.1145/3359199.
[29] Kane, S.K. et al. 2009. Freedom to Roam: A Study of Mobile Device Adoption and Accessibility for People with Visual and Motor Disabilities. *Proceedings of the 11th International ACM SIGACCESS Conference on Computers and Accessibility* (New York, NY, USA, 2009), 115–122.
[30] Lee, J.S. et al. 2015. TalkingCane: Designing Interactive White Cane for Visually Impaired

People's Bus Usage. *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services Adjunct* (New York, NY, USA, 2015), 668–673.
[31] Liu, H. et al. 2015. iSee: Obstacle Detection and Feedback System for the Blind. *Adjunct Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2015 ACM International Symposium on Wearable Computers* (New York, NY, USA, 2015), 197–200.
[32] Loadstone GPS: *https://www.loadstone-gps.com*.
[33] Long, R.G. and Hill, E.W. 1997. Establishing and maintaining orientation for mobility. 1, (1997).
[34] Marston, J.R. and Golledge, R.G. 2003. The hidden demand for participation in activities and travel by persons who are visually impaired. *Journal of Visual Impairment and Blindness*. 97, 8 (2003), 475–488.
[35] McDonald, N. et al. 2019. Reliability and Inter-rater Reliability in Qualitative Research: Norms and Guidelines for CSCW and HCI Practice. *Proceedings of the ACM on Human-Computer Interaction*. 3, CSCW (2019), 1–23.
[36] Meers, S. and Ward, K. 2005. A substitute vision system for providing 3D perception and GPS navigation via electro-tactile stimulation. (2005).
[37] Microsoft Soundscape: *https://www.microsoft.com/en-us/research/product/soundscape/*.
[38] Nearby Explorer: *https://www.aph.org/nearby-explorer/*.
[39] Ohn-Bar, E. et al. 2018. Variability in reactions to instructional guidance during smartphone-based assisted navigation of blind users. *Proceedings of the ACM on interactive, mobile, wearable and ubiquitous technologies*. 2, 3 (2018), 1–25.
[40] Pal, J. et al. 2017. Agency in Assistive Technology Adoption: Visual Impairment and Smartphone Use in Bangalore. *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, 2017), 5929–5940.
[41] Panëels, S.A. et al. 2013. Listen to It Yourself!: Evaluating Usability of What's Around Me? For the Blind. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (New York, NY, USA, 2013), 2107–2116.
[42] Saha, M. et al. 2019. Closing the Gap: Designing for the Last-Few-Meters Wayfinding Problem for People with Visual Impairments. *Proceedings of the 21st International ACM SIGACCESS Conference on Computers and Accessibility* (2019).
[43] Saha, M. et al. 2019. Project Sidewalk: A Web-based Crowdsourcing Tool for Collecting Sidewalk Accessibility Data At Scale. *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, 2019), 62:1--62:14.
[44] Saldaña, J. 2015. *The coding manual for qualitative researchers*. Sage.
[45] Seeing AI: *https://apps.apple.com/us/app/seeing-ai/id999062298*.
[46] Seeing Assistant Move: *http://seeingassistant.tt.com.pl/move/*.
[47] Seeing Eye GPS: *https://apps.apple.com/us/app/seeing-eye-gps/id668624446*.
[48] TapTapSee: *https://taptapseeapp.com*.
[49] Trekker Breeze: *https://afb.org/aw/10/2/16127*.
[50] Victor Reader Trek: *https://store.humanware.com/hus/victor-reader-trek-talking-book-player-gps.html*.
[51] Voice guidance in Maps, built for people with impaired vision: *https://www.blog.google/products/maps/better-maps-for-people-with-vision-impairments/?utm_source=feedburner&utm_medium=feed&utm_campaign=Feed%3A+blogspot%2FMKuf+%28The+Keyword+%7C+Official+Google+Blog%29*.
[52] Williams, M.A. et al. 2014. "just let the cane hit it": how the blind and sighted see navigation differently. *Proceedings of the 16th international ACM SIGACCESS conference on Computers & accessibility - ASSETS '14* (New York, New York, USA, New York, USA, 2014), 217–224.
[53] Williams, M.A. et al. 2013. "Pray Before You Step out": Describing Personal and Situational Blind Navigation Behaviors. *Proceedings of the 15th International ACM SIGACCESS Conference on Computers and Accessibility* (New York, NY, USA, 2013), 28:1--28:8.
[54] Willis, S. and Helal, S. 2005. RFID information grid for blind navigation and wayfinding. *Ninth IEEE International Symposium on Wearable Computers (ISWC'05)* (2005), 34–37.
[55] Xu, J. et al. 2019. DarkReader: Bridging the Gap Between Perception and Reality of Power Consumption in Smartphones for Blind Users. *The 21st International ACM SIGACCESS Conference on Computers and Accessibility* (New York, NY, USA, 2019), 96–104.

[56] Yelp: *www.yelp.com*.
[57] Zhao, Y. et al. 2018. “It Looks Beautiful but Scary”: How Low Vision People Navigate Stairs and Other Surface Level Changes. *Proceedings of the 20th International ACM SIGACCESS Conference on Computers and Accessibility* (New York, NY, USA, 2018), 307–320.