“It Looks Beautiful but Scary”: How Low Vision People Navigate Stairs and Other Surface Level Changes

Yuhang Zhao, Elizabeth Kupferstein, Doron Tal, Shiri Azenkot

Jacobs Technion-Cornell Institute, Cornell Tech, Cornell University, New York, NY

{yz769, ek544, dt97, shiri.azenkot}@cornell.edu

ABSTRACT

Walking in environments with stairs and curbs is potentially dangerous for people with low vision. We sought to understand what challenges low vision people face and what strategies and tools they use when navigating such surface level changes. Using contextual inquiry, we interviewed and observed 14 low vision participants as they completed navigation tasks in two buildings and through two city blocks. The tasks involved walking in- and outdoors, across four staircases and two city blocks. We found that surface level changes were a source of uncertainty and even fear for all participants. Besides the white cane that many participants did not want to use, participants did not use technology in the study. Participants mostly used their vision, which was exhausting and sometimes deceptive. Our findings highlight the need for systems that support surface level changes and other depth-perception tasks; they should consider low vision people’s distinct experiences from blind people, their sensitivity to different lighting conditions, and leverage visual enhancements.

Author Keywords

Low vision; surface level changes; depth perception; stairs; curbs; navigation; mobility.

INTRODUCTION

According to the World Health Organization, an estimated 217 million people are living with moderate to severe vision impairment causing *low vision* [1]. Low vision is a condition where one has a visual impairment that adversely affects daily activities and cannot be corrected with glasses or contact lenses [15]. Unlike blind people, however, people with low vision have functional vision, and prior work has shown that people with low vision use their vision extensively in daily activities [53,54,65].

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for components of this work owned by others than ACM must be honored. Abstracting with credit is permitted. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee. Request permissions from Permissions@acm.org.

ASSETS '18, October 22–24, 2018, Galway, Ireland

© 2018 Association for Computing Machinery.

ACM ISBN 978-1-4503-5650-3/18/10...\$15.00

<https://doi.org/10.1145/3234695.3236359>

Mobility is critical but challenging for people who have low vision. One important aspect of mobility is navigating *surface level changes*, which include any change in the height of the ground or floor such as stairs, curbs, and potholes; they are abundant both in- and outdoors, in the built and natural environment. When walking from one place to another, people must detect surface level changes (or lack thereof) and assess their distance and depth to walk safely and effectively. This requires good depth perception, which can be difficult for people with various low vision conditions [32]. Failing to detect surface level changes can be extremely dangerous. Studies have shown that people with vision loss experience falls and injuries at much higher rates than their sighted counterparts [5,11].

While a lot of accessibility research has aimed to support mobility, little to no work addressed surface level changes in particular. The standard tools for perceiving surface level changes are the white cane and guide dog [38,64]. While many advocate for these tools and praise their effectiveness [58], such tools provide a limited amount of information: The cane is essentially a pinhole through which people can get tactile information about a surface up to a few feet ahead of them. Moreover, many people with low vision prefer not to use a cane. With the growing ubiquity of depth sensors, we have the opportunity to design novel tools that provide much more information about surface level changes, augmenting if not replacing traditional tools.

To inspire technology design, we sought to understand the experience of people with low vision when navigating surface level changes. We conducted a study to explore what challenges low vision people face, what tools they use, and what strategies they employ to negotiate this important aspect of mobility. Prior work by Szpiro *et al.* [54] found that most low vision participants preferred using their vision over using a white cane during navigation, and lighting conditions affected their ability to notice obstacles, uneven pavement, and other people. However, this research lacks details on how low vision people perceive and deal with surface level changes. As such, another study is essential to set the foundation for designing systems to support their mobility.

We conducted a contextual inquiry study with 14 people with low vision, observing them in a set of navigation tasks in- and outdoors. Since we focused on surface level changes, we chose tasks that included walking up and down four different sets of stairs (an emergency exit staircase,

two indoor access staircases with distinct designs, and a set of outdoor steps), curbs, and two city blocks. Following the contextual inquiry method [7], we observed participants' behaviors in each navigation task and asked them questions to understand what they perceived and thought.

We found that navigating stairs and curbs were the most challenging mobility-related tasks for the low vision participants. Most relied on their vision to navigate surface level changes, but faced severe difficulties because of certain features in the environment design. With ineffective binocular vision, participants used different monocular cues to identify surface level changes, such as lighting and shading, color or texture changes, and occlusion cues. However, color or texture changes on flat surfaces generated illusions of depth changes that confused the participants. Moreover, while participants walked outdoors and crossed streets with relative ease, low obstacles and indoor glass walls were extremely challenging. Some participants used a white cane when navigating surface level changes, but all were uncomfortable and even afraid. No tools adequately addressed their needs in this task.

In summary, we contribute the findings from a study that reveals the experiences of people with low vision in navigating surface level changes, a critical aspect of mobility, and discuss design considerations for designing navigation technologies for people with low vision.

BACKGROUND: ACCESSIBILITY BUILDING CODES

While people are generally familiar with legal requirements of access ramps for wheelchair users, much fewer people are aware of regulations that affect people with visual impairments. We provide an overview of accessibility regulations relating to surface level changes that may impact low vision people to better understand how our study findings relate to widespread standards.

In the United States, building codes are regulated by many levels of government, from the federal and state governments to the municipality in which a building stands. Federal regulations are detailed in the Americans with Disabilities Act (ADA). According to the ADA, "Accessibility" refers to the accommodation of physically challenged people in structures [2]. This includes ground surfaces and stairways. The ADA standards for stairways only apply to stairs that are a part of a "means of egress," a continuous unobstructed path to enter or leave a building. The ADA specifies that all such stairs on a flight of steps shall have uniform riser heights (the vertical height of the step, Figure 1) and uniform tread depths (the horizontal area where the foot is placed). Open risers are not permitted. Figure 1 illustrates the stair components.

The ADA advises, but does not require, providing visual contrast on the tread nosing (the leading edge of the stair tread), to make the stairs more visible to people with low vision. However, there is no information indicating what kind of contrast is beneficial.

Figure 1. Stair structure and the basic components.

Below the federal level, most jurisdictions in the US have adopted the International Building Codes (IBC) [29] for non-residential buildings. The IBC includes codes on handrails in staircases, stating that at the top of the stair flight, handrails shall extend horizontally above the landing for at least 12 inches from directly above the top riser. At the bottom of a stair flight, handrails shall extend at the slope of the stair flight for a horizontal distance at least equal to one tread depth beyond the bottom riser.

The regulations are limited, most focus on people who use wheelchairs and largely neglect low vision people's needs. Importantly, the ADA regulations only apply to egress stairs, and other staircases are not regulated.

RELATED WORK

Mobility and Blind People

Researches have studied the experiences of blind people during navigation [24,25,63,64]. Williams *et al.* [64] conducted a phone interview to ask 30 visually impaired participants about their challenges and use of aids during navigation. They found that blind navigators used their cane or guide dog as the main navigation aid, and varied in the way of using smartphone navigation technology. In another study that used focus groups and journal entries, Williams *et al.* [63] asked blind participants about their social interactions with sighted people during navigation, finding that navigation-specific language and reasoning differed greatly between sighted and visually impaired people.

Researchers have designed a wide variety of navigation systems for blind people in recent years. Many systems focused on way-finding for indoors (*e.g.*, [34,45,67]) or outdoors (*e.g.*, [4,10,13,25,36,39]). Meanwhile, some systems aim to assist visually impaired people with obstacle avoidance (*e.g.*, [1,19,35,57]). By recognizing obstacles via sensors such as cameras and range finders, these systems provided audio [3,41,50] or tactile feedback [1,12,40,51,56] to notify blind users of the existence and distance of obstacles. Some researchers even augmented the white cane with sensors to detect obstacles that were beyond the cane's reach [42,52,60]. However, no obstacle avoidance systems have been widely adopted—the traditional white cane and guide dog are still the main mobility aids for blind people [38,64].

These systems focused on people without vision, providing no-visual feedback, which may not suit the unique needs of low vision people who have functional vision.

Mobility and Low Vision People

Recently, researchers have studied the unique experiences of people with low vision in different daily activities, including their use of computing devices [53] and vision enhancement technology [68], and shopping and wayfinding [54]. Some have also designed assistive technology to facilitate certain tasks (e.g., reading [65], visual search [37,66]). Below we describe low vision research related to mobility, the general topic of our work.

Studies on Mobility and Low Vision

Several studies have shown that reductions in visual acuity, visual field, contrast sensitivity, or depth perception impeded independent navigation and mobility [6,9,16,43,46,62]. For example, a study by Leat and Lovie-Kitchin [32] showed that visual field loss greatly impacted walking speed while reduced visual acuity and contrast sensitivity had a bigger impact on distance and depth detection. West *et al.* [62] found that people with low acuity and low contrast sensitivity reported being slower walking up and down stairs and walking short distances. With these mobility challenges, it is no surprise that multiple studies found that low vision people have a greater risk of mobility-related accidents such as falls than sighted people [11,17,18,22,26,27,55].

Among mobility tasks, stair detection is one of the most dangerous challenges low vision people face [5]. Failing to detect descending stairs was more dangerous and had a higher correlation with falls than failing to see obstacles or ascending stairs [33]. Bibby *et al.* [8] surveyed 30 low vision participants about their performance in mobility tasks. They found that participants gave higher difficulty scores to tasks that involved surface level changes, such as walking on curbs and descending stairs.

In the human-computer interaction literature, however, there has been little work on understanding low vision people's navigation experiences and needs. Szpiro *et al.*'s research [54], which used contextual inquiry to observe low vision people's behaviors as they navigated to find a nearby pharmacy, is the only work in this area to our knowledge. They found that low vision people struggled but heavily relied on their vision during navigation. Participants used GPS-based applications on smartphones for wayfinding and orientation, but had difficulty interacting with their devices. Szpiro's work mainly focused on wayfinding. It did not address the equally important but more low-level aspects of mobility such as the perception of surface level changes.

Low Vision Technology for Mobility

A majority of the specialized devices for low vision are optical devices. Bioptics, monoculars, telescopes and binoculars are used for spotting signs and obstacles in the distance [59]. Prisms can be ground into glasses or added

temporarily on to glasses to help manipulate the field of view. These specialized devices often stigmatize users in social settings [49], and many avoid using them or abandon them altogether [20].

Some researchers have designed navigation systems for low vision [21,28,47]. For example, Everingham *et al.* [21] designed a neural-network classification algorithm for a head-mounted device that segmented scenes rendered in front of users' eyes and recolored objects to make obstacles more visible. Hicks *et al.* [28] built a real-time head-mounted LED display with a depth camera to aid navigation by detecting the distance to nearby objects and changing the brightness of objects to indicate their distances. However, these systems applied "signal to signal" image processing technology to users' vision, without considering the various visual abilities and needs that low vision users may have. A deeper investigation of how low vision people navigate the environment is needed, to understand their perception and needs, to inspire effective and socially acceptable navigation systems.

Cues for Depth Perception

Navigating surface level changes involves depth perception. Sighted people use both monocular and binocular cues to perceive depth [14]. Monocular cues include but are not limited to: the relative size cue [30], the occlusion cue (the partial occlusion of one object behind another), and the lighting and shading cue (the way light falls on the environment and reflects off its surfaces that create shadows and highlights) [61]. Meanwhile, binocular cues include Convergence and Stereopsis. Convergence refers to that the movement of the extraocular muscles that enables the eyes to look at the same point in space creating a kinesthetic sensation of depth perception [44]. Stereopsis is the ability to use two images of the same scene from slightly different angles to judge depth [14]. Decrease in visual acuity and the disparity of vision between the two eyes in people with low vision impacts their ability to use binocular depth cues [14,31].

To our knowledge, no prior work explored the visual cues that low vision people use to perceive depth. Our study shed light on their depth perception by understanding their experiences with surface level changes.

METHOD

Participants

We recruited 14 participants with low vision (7 female, 7 male), whose ages ranged from 28 to 70 (mean=43.3). All but one (Tami) reported that they were legally blind, meaning that either (1) their best-corrected visual acuity in their better eye was 20/200 or worse, or (2) their visual field was 20 degrees or narrower¹. No participants had been to

¹According to the New York State Commission for the blind, one is permitted to apply for legal blindness when her visual acuity is better than 20/200 if (1) the visual condition is progressive, and (2) she needs aid to continue working.

Pseudo-nym	Age/ Sex	Diagnosis	Visual Acuity	Visual Field (test)	Color Vision	Mobility Aids
Luke	70/M	Glaucoma in right eye; Total vision loss in left eye from trauma	20/200	Full in right eye; no vision in left eye	Good	Use a cane at night and in unfamiliar places
Maria	61/F	Retinopathy of prematurity	20/400	Full	Good	New and seldom cane use
Uma	57/F	Posterior Uveitis	20/200	Constriction	Deteriorating	No mobility aids
Kacee	29/F	Albinism	20/200	Full	Good	Use a cane at unfamiliar places
Matt	54/M	Flecked retina syndrome; central scotoma	20/200 left; 20/400 right	Full	Good	No mobility aids
Sophia	33/F	Stargardts	20/100- 20/200	Full in right eye; constriction left eye	Deteriorating	No mobility aids
Kaila	28/F	Macular Degeneration	20/800 left; 20/600 right	Constriction	Deteriorating	Cane
Andy	48/M	Achromatopsia	20/400	Full	Color blind	No mobility aids
Jason	55/M	Cone rod dystrophy	20/200	Full with nystagmus	Good	New cane user
Harry	56/M	Cone dystrophy	20/200	Full in right eye; constriction in left eye	Color blind	Use a cane only for traveling outdoor
Polly	65/F	Retinopathy of prematurity; Glaucoma	20/400	Constriction	Deteriorating	Use a cane for only unfamiliar places
Eddy	35/M	Albinism	20/100 left; 20/200 right	Full	Good	An identity cane
Tami	64/F	Cone dystrophy	Better than 20/200	Full in right eye; constriction in left eye	Color is no longer bright	New cane user; only use at night when alone
Jacob	47/M	Stargardts	20/200	Full	Deteriorating	Seldom cane user

Table 1. Demographic information of the 14 low vision participants. Except for the visual field that was tested in the study, all the other information was self-reported.

our study environment before this study. We recruited participants via Facebook groups and email lists that discuss vision-related issues. When a potential participant contacted the research team, we conducted a brief phone screen where we asked about visual condition and technology use to ensure the participant was indeed low vision (not sighted or blind).

Procedure

The study consisted of a single session that lasted 1 to 2 hours. The session included a structured interview and an observation of participants performing a set of navigation tasks. During the interview, we asked participants about demographics, their visual condition, and their experience with technology. A licensed optometrist, one of the researchers on the team, conducted a confrontation visual field test to determine whether participants had visual field loss that could substantially hinder their mobility. Table 1 shows participants demographics, self-reported information about visual ability, and the results of the visual field test.

The navigation tasks were conducted at different locations across two buildings (we refer to them as building B and building T) on our university campus and two city blocks. Below are the tasks in the order they were performed:

- Tasks 1-2: Walk up and down one floor on an indoor decorative curved staircase in building B (Figure 2A).
- Tasks 3: Walk from the curved stairs to an emergency exit staircase in building B.
- Tasks 4-5: Walk down and up one floor on the emergency exit staircase in building B (Figure 2B-2C).

- Task 6: After exiting building B, locate the entrance to Building T and walk there.
- Task 7-8: Walk up and down one floor on an indoor decorative wooden staircase in building T (Figure 2D).
- Task 9: After leaving Building T, walk down a set of two steps in an outdoor plaza (Figure 2E).
- Task 10: Cross a street.
- Task 11: Walk two blocks down a city street.

During each task, We followed the master-apprentice relationship model of contextual inquiry [7]. We observed participants' behaviors during the task and asked them to "think aloud." After the task was completed, we asked about their experience, including their challenges and reasons for their behaviors. For tasks involving stairs, we also asked how their experience compared to other stair tasks in the study. For longer tasks (Tasks 6 and 11), we asked participants to stop and conversed briefly if we observed something interesting.

Environment

The buildings used in the study were completed in 2017, built in a modern architectural style with large windows and glass walls. We introduce the environment for all the tasks.

The stairs participants navigated included: (a) Decorative curved stairs (Figure 2A, Tasks 1-2): gray treads with white contrast strips; dark blue riser; beside a large window. (b) Emergency exit stairs (Figure 2B-2C, Tasks 4-5): tan treads with dark gray contrast stripes; dark gray risers; having two steps on the landing where the stairs turn (Figure 2B); no window. (c) Decorative wooden stairs (Figure 2D, Tasks 7-8): stair riser and tread in wooden texture; thin metal

Figure 2. Stairs in the study: A. indoor decorative curved stairs; B. Emergency exit stairs part I: two steps at the landing; C. Emergency exit stairs part II: two sets of stairs with a landing; D. indoor decorative wooden stairs; E. outdoor stairs.

stripes; facing a large window. (d) Outdoor stairs (Figure 2E, Task 9): white steps with three engraved stripes at the edge of the tread; no handrail.

Other navigation environments included: (a) Indoor navigation (Task 3): passing by tables, chairs, a small piece of exercise equipment as a low obstacle (Figure 7A), and some glass walls (Figure 7B). (b) Navigation between buildings (Task 6): flat ground with color and texture changes. (c) The two city blocks (Tasks 10-11): including curbs, curb cuts, various sidewalks with different texture, as well as pot holes and sewer drains.

Analysis

For each study session, one researcher interacted with the participant while another recorded the participant with a handheld video camera. We sent the video recordings to a professional transcription service that transcribed the audio. The researchers reviewed the video recordings to identify participants' behaviors and the aspects of the environment they referred to during the study.

Two researchers analyzed the transcripts using qualitative coding methods based on grounded theory, as described by Glaser and Strauss [23], Saldana [48]. The two researchers coded two sample transcripts independently, and compared and discussed the codes together. A codebook was created based on the agreement of the two researchers. The codes were then categorized into themes using affinity diagrams and axial coding. One researcher coded the rest of the transcripts based on the agreed codes and categories.

FINDINGS

Reactions to Surface Level Changes

Navigating surface level changes, especially curbs and stairs, was a major challenge for all participants. They told us of times they fell and injured themselves when walking on curbs or stairs. Tami described her experience with curbs: "I had a lot of injuries because I fell down. I've always been a very, very, fast walker, but now I've fallen off curbs."

These experiences lead participants to feel uncomfortable, frustrated, and embarrassed when walking on stairs and curbs. Some expressed their fear. Maria explained that walking down stairs "deserves [her] full attention because of [her] fear of falling down. Even though [she] can see all

the steps, it doesn't matter. It's just the fear of it." Other participants (e.g., Andy, Eddy) were embarrassed of falling in public since it would affect how others perceived them. As Andy explained, "I did fall down a pair of steps recently at a restaurant. I didn't injure my self but it was enough to be embarrassing. I'm very careful in social situations."

Technologies Used

All participants except for Jason had a smartphone and used different applications on their computers (e.g., ZoomText) and smartphones (e.g., SeeingAI, BlindSquare).

Although participants used these high-tech tools in their daily lives, none used digital devices or applications throughout the study. Nine participants used smartphone map applications (Google Maps or Apple Maps) for wayfinding and orientation outdoors. However, participants emphasized the need for tools that would help them detect surface level changes or obstacles. Matt explained that one of his major needs was not addressed by the technology available to him today:

"I used Google maps, but I haven't found it very useful. My problem is that, because of my central scotoma getting worse, I don't always see what's directly in front of me. Coming downstairs is very important because I tend to miscount the stairs. [The map application] is telling me walk this way, turn this way. It's more annoying than useful since it's easier to figure out where I am [than to detect stairs]" (Matt, 54).

In our study, the only tool used for navigating surface level changes was a cane. One participant (Kacee) told us she sometimes used a flashlight at night while walking, which could potentially help with surface level changes. Three participants used a cane frequently, six had a cane but only used it at night or in new or challenging places, one had an identity cane (i.e., a slim white cane intended not for walking assistance but rather to let others know its carriers are visually impaired). The other four participants did not have a cane. Only four participants (Luke, Kacee, Kaila, Jason) used their cane in our study.

Some participants felt more confident when using the cane since it helped them detect surface unevenness and obstacles. Kacee explained that the cane reduced cognitive load and freed her to attend to a conversation:

“I don’t want to spend my whole life looking down. I just feel like I can walk more confidently if I hold my cane in the front. I feel like a more professional person. I can actually carry on a conversation with somebody, not worry so much about where I’m going” (Kacee, 29).

Participants all commented on the fact that a cane was a powerful social signal that they have a disability. Some participants found this helpful (people wouldn’t cut in front of them) while others did not want to attract extra attention to themselves. Eddy explained that, “We try to fit in so hard that we are almost embarrassed to walk around with [the cane].” Instead of a cane, he wanted technology that was less intrusive, “I’m so bent on devices that are low profile, that looks like something else. I’m trying not to be noticed.”

Experiences with Different Staircases

Participants’ experiences varied significantly across the different sets of stairs. In general, most found the curved and wooden staircases to be more challenging than the emergency exit stairs. While the former two staircases look beautiful, six participants were dismayed that aesthetics were prioritized far beyond accessibility.

“It looks so nice, and most people like myself [who are low vision], I mean, I care about aesthetics. However, the stairs are not the friendliest ever. These stairs are a perfect example. They’re just not fully friendly for the in between person. A blind person it doesn’t matter because they’re holding onto the rail, but, someone like me, that depends on my sight a lot, I don’t like these stairs” (Eddy, 35).

Curved Staircase (Tasks 1-2)

Several design elements in these stairs made them more accessible than the other staircases. The contrast stripes were visible, and the risers and treads were painted in different colors, which made it easier to detect the stair edge when walking upstairs. However, the curviness and the width of the treads (nonstandard design elements) caused feelings of uncertainty.

The major challenge of the curved staircase was that, at the bottom of the stairs, there was an extra contrast stripe on the landing that generated the illusion of another step (Figure 3B). We explain participants’ experience and why the extra stripe fooled them easily in the “Contrast Stripe” Section.

Emergency Exit Stairs (Tasks 4-5)

Most participants (9 out of 14) felt that the emergency exit stairs were the easiest to navigate since they were simple without any visual distractions. Participants who were sensitive to light felt more comfortable with the lighting conditions since there are no windows. Sunlight from windows can be distracting.

However, some participants also had difficulty navigating these stairs. Five participants felt the lighting was insufficient, which reduced the visibility of the contrast stripes, making it hard to detect the stair edges. They had to feel for the edge of a stair with their feet. Jason did not use

his cane at the curved stairs but decided to use it at these stairs. Moreover, three participants were confused with the structural design, which included two steps at the landing that connects two flights of stairs (Figure 2B). They did not expect these stairs easily and felt they could have fallen.

Wooden Staircase (Tasks 7-8)

Twelve participants agreed that the wooden stairs were the most challenging in the study. The riser and tread of the stairs had the same wooden texture, and the contrast stripes were thin metal strips. This gave participants the impression that “everything [was] all the same” (Polly). Moreover, the varying color of the wood (Figure 2D) generated the illusion of edges in the riser and tread. As a result, participants were much more cautious when walking on the wooden stairs. Kacee and Eddy only held the railing when walking on these staircases and Jacob had to lightly kick each step with his foot to detect the edge of each stair when walking up.

Moreover, as the wooden stairs faced a large window, the visibility of the stairs depended on the lighting conditions outside and whether participants were facing the light: the tread and riser were hard to distinguish when there were no shadows cast on the riser, and the metal strips were only visible when reflecting bright light.

Outdoor Decorative Stairs (Task 9)

The outdoor stairs were the hardest for participants to detect. Except for Uma, none of the participants detected the stairs from over a foot away. Harry stopped at the top stair and looked down, “I couldn’t tell [there were stairs] until here. This really threw me off. I would have bet you a million dollars that there was no steps here but there are.”

Contrast Stripes

While contrast stripes are “advised” by ADA guidelines, there is no explanation of how they should be designed. In our study, we found that only the stripes on the curved stairs were helpful because they were wide and had high color contrast. The stripes on the other stairs were generally challenging for most participants.

Stripe Contrast. The contrast of a stripe is vital for its detection and usefulness. For some participants (Harry, Andy), luminance contrast that generated a difference in brightness was more effective than color contrast. While not seeing the stripes on all other stairs, Harry who was colorblind was able to see the reflection from the metal stripes on the wooden stairs. Andy suggested using illuminated stripes: “The movie theatres have the little light stripes on the stairs, that’s one of the situations where the contrast is good.”

Stripe Placement. Participants used the stripes to locate the step edge. However, both the stripes on the curved staircase and the wooden staircase were positioned several inches away from the edge (Figure 3A), which misled the participants. Moreover, some participants felt that having a stripe on each step distracted them and brought them more

trouble with depth perception. Jason and Tami preferred having stripes only on the first and last steps.

Figure 3. Contrast stripes: A. the metal stripes on the wooden stairs; B. extra contrast stripe at the curved stairs.

Extra Stripes. Both the curved stairs and the wooden stairs had an extra contrast stripe on the landing (Figure 3B). All participants slowed down to look carefully, and some even used their feet or cane to test if it was a step. Maria, Andy, and Harry thought it was a real stair and tripped a little bit.

With reduced binocular depth perception, participants relied on monocular cues, such as color changes, to deduce depth changes. Thus, when they learnt that contrast stripes marked each step, they associated each stripe with a step, including the extra stripe, which made them trip. “When coming down the stairs, I’d have told myself that each stripe is a step. In my brain I see the stripe, I’m going to treat all these stripes as a step down” (Eddy).

Information Sought

Participants sought certain information when navigating stairs.

Stair Existence. Detecting stairs from several feet away was challenging for participants, especially when approaching downstairs. Even when standing right in front of a staircase, many participants perceived it as a flat surface. Polly described her visual experience when looking at the wooden staircases:

“I can see a little bit, but I wouldn’t think of this as steps. Have you ever been in places where they have these accordion floors, like when you pass through a tunnel inside of a building? It’s like a pedway, and the floor of the pedway has these lines [metal stripes] on it. I felt like it was a trick played on my brain. To me this could be a floor, a wooden floor with these lines in it” (Polly, 65).

Stair Overview. All participants, except for Maria and Sophia, carefully looked around to perceive the structure of the environment before walking on stairs. They wanted to know whether the stairs were going up or down, the number of stairs, and whether there was a landing or a turn. However, this was challenging and not always possible.

First and Last Stair. All participants felt that locating the first and last stairs were the most important but challenging tasks. By knowing where the first stair was, participants built a mental model about the stair dimensions and extrapolated this knowledge to the rest of the stairs. As Jacob mentioned, “The regular steps are always the same. Once I’ve taken the first step, I’ve secured myself how

these steps are. My brain already knows what to do, and I’m OK with the rest of the stairs.”

Stair Height. Knowing about the height of a stair was important for safety. In our study, ten participants estimated the step height by using their vision or their cane.

Behaviors on the Stairs

We describe participants’ behaviors when navigating stairs.

Slowing down or stopping

Afraid of falling, participants were cautious when walking on stairs. We observed that all participants slowed down or even stopped at some point to carefully perceive the stairs during navigation. Mostly, they slowed down before the start and end of the stairs to look for the first and last step. Three participants (Luke, Maria, and Kaila) stepped on each stair at a time with both feet at challenging staircases.

Looking for clues

Participants used distinct clues in the environment to understand how the staircase was structured: where it began, whether it went up or down, and where it ended.

Riser. Stair risers, which often have a different color than a stair tread, were a useful visual cue for all participants. They are only visible when walking upstairs though. The wooden staircase was so difficult to navigate partly because the riser and tread were the same color.

Railing. Interestingly, participants used the railing as a visual cue as well as a tactile cue. The bends at the beginning and the end indicated the beginning and the end of the stairs, while the slope indicated the direction of the stairs (up or down).

Shadows. Since many of the participants had difficulty distinguishing colors, luminance contrast was the main clue they relied on as opposed to color contrast. Shadows, which have high luminance contrast, were thus an effective visual cue. Participants identified stairs by seeing the shadows on the risers and treads of the stairs (Figure 4A). However, sometimes shadows caused the illusions of stairs. The shadows of the railings cast on the landing at the industrial stairs formed several darker lines in parallel (Figure 4B). As Kacee said, “This is really freaky.”

Figure 4. Shadows: A. shadow of the riser cast on stair tread; B. shadow of the railing generating illusion of steps.

People. Besides the physical environment, four participants observed other people to understand surface level changes. As Uma said, “I know [it’s downstairs] because people are

going down. I watch the people, and I watch their feet. I see what they are doing, and that's what I have to do as well."

Looking down

Five participants always looked down at their feet or the next step even when going upstairs. "I typically look down. Just making sure that I'm not overstepping, just makes me pace myself" (Sophia). Six participants felt confident and looked ahead when going upstairs, but they looked down much more when going downstairs. Matt and Jacob only looked down when they approached the first or last stairs.

Counting Stairs

Six participants mentioned that they sometimes counted and memorized the number of stairs, especially in places that they would travel often. Kaila also used the number of steps to identify a specific set of stairs, double-checking whether she's on the right path.

Tactile Feedback

Besides visual information, participants used their hands, feet, and cane to get tactile feedback from the stairs.

Railing. Twelve participants held the railing for balance and safety even though they could see the stairs. Some participants also felt the shape of the railing to understand the stairs. By feeling the turn and the slope of the railing, they could understand where the stairs start and end, as well as the direction of the staircase. As Polly said, "I put my hand a little bit ahead I can feel it going down, and I know to step down. I know the minute there's a turn on the banister, the first step is coming."

However, the railing was not always reliable and poor design could pose challenges. For example, the turn of the railings at the wooden stairs did not match the positions of the top and bottom steps. It bended both before the stair starts and after the stair ends. This confused the participants and made them think that there were extra steps.

Feeling with Feet. We found that all participants used their feet to feel the surface when they were uncertain about the depth change. They kicked the step when walking up or drag their feet over the step edge when walking down. "I'm dragging my feet along on purpose. My feet are giving me information [about the steps]. That's why I love flexible shoes" (Eddy). Mostly participants only used their feet to locate the first and last step rather than each step.

Feeling with a Cane. Four participants used their cane during our study. Interestingly, when walking downstairs, the cane was only used for detecting the end of the stairs. Participants angled the cane one step ahead of their body, so that the cane would not hit the ground until they arrived at the landing. When the cane tapped the floor, it indicated that the stairs came to an end. Besides detecting the stair position, some participants (e.g., Jason) used the cane to gauge the step height. They tapped the stair riser by holding the cane vertically with the cane tip on the floor and

estimated the stair height by feeling the touch point between the stair edge and the cane.

Multiple Senses

While being able to perceive information with their vision, participants wanted to use other senses to feel more secure and reduce cognitive load. Maria described how she studied the first step with both visual and tactile feedback, "I'm using the visual means, but I'm using more than vision. I'm using the kinesthetic sense of the depth of the step. I also use tactile cues like this, the railing curve here." Using only their vision, some felt, was exhausting.

While using multiple senses, we found that most participants relied on and preferred using their vision during navigation, only using other senses as backup. As Matt said, "The tactile and the audio is to supplement the visual but the visual is still being used."

The four participants who used the cane in our study also used their vision a lot and wanted to use their vision often. "I'm always gonna [look at the stairs], because it's a visual thing. And even though I have the cane, I'm still trying to see as well as use the cane" (Jason). Luke switched between using vision and the cane at different stairs during the study. He felt that the cane and the vision were equally important for him. Before walking on stairs, he scanned the environment to decide which sense he would rely on.

Other Surface Level Changes

Walking on Curbs (Task 10)

Curbs were more challenging than stairs because they were harder to detect and did not have railings. "[When walking on stairs], if I fall, I have railings that I can hold on to. But a curb is hard. That's one of the things that I'm really scared about" (Uma).

Participants used different strategies to detect curbs. Harry, Eddy, and Jacob used occlusion cues to detect the curb: they looked at the car wheel by the curb, and decided there's a curb because the lower part of the wheel was blocked. Harry looked for shadows to deduce a curb, such as the shadow of the curb cast on the street, and the shadow of a tree branch that bends over the curb. However, he explained that too many shadows might be more distracting than helpful.

Figure 5. A. Curb highlight; B. a curb cut with tactile domes.

Participants' opinions differed about the painted highlights on the curbs that marked parking areas (Figure 5A). Five participants thought these were helpful for indicating the

location of the curbs. However, three participants interpreted these to mean that there was a sloped surface and not a curb. Regardless of interpretations, the highlights, especially the yellow ones, were visible cues.

Crossing the street (Task 10)

All participants preferred walking on a curb cut as opposed to stepping over the curb to cross the street. They used different methods to locate the curb cuts. Ten participants looked for the crosswalk lines, which guided the location of the curb cut (Figure 5B). Some curb cuts had tactile domes that were darker in color. With this contrast, participants could even locate the curb cuts at a distance.

Walking outside (Task 6, Task 11)

Participants were careful walking outside, looking for small surface level changes, such as cracks, holes, or unevenness. They paid attention to all clues that might indicate surface unevenness, such as color or texture changes. During the study, we observed that most participants hesitated when they encountered a grouting line between two pieces of cements (Figure 6A) or other color or texture changes (Figure 6B). Such areas gave an illusion of a depth change:

“[The texture] change gives me an indication that there’s a change in surface. I’m alert. I want to make sure there’s not a crack or a hole. Any time there’s a change in the surface, I want to check and be familiar with what I’m going through, I guess just to be safe” (Luke, 70).

Figure 6. A. Grouting line between two ground pieces; B. the texture changes on the ground.

Obstacles (Task 3, 11)

Participants were able to see most obstacles during the navigation, including tables, chairs, fire hydrants, poles, cones, and trashcans. Most participants centered themselves in the hallway and the sidewalk since the obstacles were usually off to one side. Some participants (e.g., Uma, Matt) also observed people walking ahead to avoid obstacles.

Figure 7. A. Low obstacle: a small piece of exercise equipment on the carpet. B. glass walls.

However, low obstacles were still challenging. In the study, participants walked passed a small piece of exercise

equipment on their way to one of the staircases (Figure 7A). Most participants saw it when they were less than a few feet away. Some even used their feet or cane to touch it to verify it was an object and not an image on the ground.

Finally, the transparent glass walls (Figure 7B), which functioned as large obstacles, irritated all participants. Because of the transparency and the reflections in the glass, participants lost their sense of space. Some participants identified the glass wall by closely looking at the edges of the wall or at decorations on the glass.

DISCUSSION

The study revealed that navigating surface level changes, especially walking downstairs, was a source of stress and fear for people with low vision, in spite of the fact that the buildings were new and complied with accessibility regulations. The ADA aimed to improve the accessibility of the built environment, “[prohibiting] discrimination against people with disabilities in public life.” Yet it fails to support people with low vision in such basic navigation tasks. Meanwhile, a set of tools, ranging from the cane to smartphone applications, were designed to support different aspects of mobility. However, while most participants were aware of such tools, they found them inadequate or undesirable for navigating surface level changes.

Design Considerations

As technology becomes pervasive in our environment, designers have an opportunity to support navigating surface level changes with artifacts that range from smartglasses, handheld devices, to technologies embedded in the environment. Based on our findings, we discuss design considerations for future navigation systems for low vision.

Information Needs. Participants used multiple senses and different strategies to collect information from the environment when navigating surface level changes. They sought four key kinds of information: (1) existence: whether there is a surface level change ahead and how far away it is; (2) overview: how the surface changes, including the change direction (up or down), and the number of stairs, if applicable; (3) position: the exact position of the surface level change, such as the curb edge and the first and last stair; (4) depth: how deep the surface level change is, such as the curb height. Future technologies should focus on providing or enhancing this information.

Visual Highlights. Visual highlights were the main cues participants used to identify surface level changes, such as the contrast stripes and curb parking highlights. Unlike tactile feedback from a cane or one’s feet, visual highlights enabled low vision people to detect the exact position of surface level changes at a distance. For example, many participants identified a curb cut using the contrasting color of the tactile domes. In addition to color contrast, luminance contrast was also effective as participants used many shadow and reflection cues to perceive depth changes. Future navigation systems should consider designing visual

highlights with color or luminance contrast to indicate surface level changes for low vision people.

Visual Abilities and Preferences. Only two visual functions, color vision deficits and light sensitivity, had some relationship to mobility patterns. Participants who had difficulty distinguishing colors (Harry, Andy) relied on luminance contrast (*e.g.*, shadows) to detect surface level changes, while participants who were sensitive to light (*e.g.*, Kacey and Eddy, who both had Albinism) felt more comfortable at the emergency stairs, which had relatively dim light. In other cases, some participants with similar visual conditions had diverse behaviors and preferences. For example, Sophia and Jacob, who both had Stargardt's with a reported visual acuity near 20/200, used different mobility tactics. Sophia preferred seeing in a darker environment and often looked down when navigating stairs, while Jacob had difficulty in the dark emergency exit stairs and only looked down at the first and last stairs. Thus, it is important for designers to consider that visual abilities do not always dictate personal preferences.

The Effect of Lighting. Lighting conditions proved to be an important factor for detecting surface level changes, as well as for other mobility tasks. While soft light was helpful, bright sunlight could hinder people's ability to perceive their surroundings. Certain technologies can also be affected by lighting conditions. For example, the effectiveness of computer vision technology may vary between outdoor and indoor locations, and the visual effects of augmented reality technology also depend on the brightness of the environment. Future technology for low vision should consider people's visual perceptions in different lighting conditions. In addition, designers should evaluate the effectiveness of the new systems in different lighting scenarios.

Design for Psychological Security. Participants were cautious and even afraid when navigating surface level changes. They slowed down on the stairs, sacrificing time for physical safety but also psychological security. Current technologies (low and high-tech) may not provide users psychological security. For example, those who used a cane in our study still preferred holding the railing to *feel* safe and confident. Thus, besides functionality, psychological security should be considered when designing assistive technology. To support walking downstairs, for example, a system could provide psychological security by recognizing the railing to help a user locate and hold on to it. However, such a design may encourage users to rely on the railings, rather than walking down the stairs like a sighted person. Supporting a user's psychological security is complex, involving many factors: a user's prior experiences, the potential consequences of an error in a given task, and the user's trust in the design in addition to the technology's reliability. Designing and evaluating for psychological security extends a traditional HCI approach, and researchers should consider this perspective moving forward.

How People with Low Vision Perceive Depth

Our research sheds light on the ways in which people with low vision perceive depth, a fundamental visual task. With reduced visual ability, participants relied on monocular cues rather than binocular cues to perceive depth information. Although using some similar monocular cues with sighted people, such as occlusion (*e.g.*, detecting a curb because it partially occluded the wheel of a parked car) and lighting and shading cues (shadows and reflections), participants mostly relied on color and texture changes as an indication of depth change. As a result, complex color or texture decorations on a flat surface were confusing and required careful inspection.

Limitations and Future Work

We conducted the study in a specific environment: two newly-constructed buildings in an urban area. Although these buildings represent recent aesthetic trends and comply with regulations, they do not represent all built environments. In the future, we will expand our study by investigating other environments. In addition, future work should complement our qualitative findings with a quantitative analysis. Specifically, we should quantitatively evaluate the effect of different environmental features on low vision people's mobility.

CONCLUSION

In this paper, we studied the experiences, challenges, and strategies low vision people had when navigating surface level changes, a critical and dangerous aspect of mobility. We conducted a study with 14 low vision people using contextual inquiry, observing their behaviors in multiple tasks, which involved different surface level changes. Our study illustrated how extensively people with low vision use their vision and the lack of current assistive technologies to improve independent travel. Our work revealed a wealth of opportunities for future research and innovations for a growing and largely ignored user group.

ACKNOWLEDGEMENT

We thank Karla Polo-Garcia who drew the stair structure figure. This work was supported in part by the National Science Foundation, under grant no. IIS-1657315 and the K. Lisa Yang and Hock E. Tan Institute on Employment and Disability in the Cornell University ILR School.

REFERENCE

1. Ziad O Abu-Faraj, Elie Jabbour, Paul Ibrahim, and Anthony Ghaoui. 2012. Design and development of a prototype rehabilitative shoes and spectacles for the blind. In *2012 5th International Conference on Biomedical Engineering and Informatics, BMEI 2012*, 795–799. <https://doi.org/10.1109/BMEI.2012.6513135>
2. ADA. 2010. ADA Standards for Accessible Design. Retrieved April 16, 2018 from https://www.ada.gov/2010ADASTandards_index.htm
3. Daniel Aguerrevere, M Choudhury, and A Barreto. 2004. Portable 3D Sound / Sonar Navigation System

- for Blind Individuals. In *2nd LACCEI Int. Latin Amer. Caribbean Conf.* Retrieved April 14, 2018 from [http://www.laccei.org/LACCEI2004-Miami/papers - PDF/ST054_ Aguerrevere .pdf](http://www.laccei.org/LACCEI2004-Miami/papers-PDF/ST054_Aguerrevere.pdf)
4. Dragan Ahmetovic, Cole Gleason, Chengxiong Ruan, Kris Kitani, Hironobu Takagi, and Chieko Asakawa. 2016. NavCog: A Navigational Cognitive Assistant for the Blind. In *Proceedings of the 18th International Conference on Human-Computer Interaction with Mobile Devices and Services*, 90–99. <https://doi.org/10.1145/2935334.2935361>
5. J C Archea and Med Clin Geriatr. 1985. Environmental Factors Associated with Stair Accidents by the Elderly. *Clinics in geriatric medicine* 1, 3: 555–569. Retrieved March 26, 2018 from <http://www.ncbi.nlm.nih.gov/pubmed/3830385>
6. Sue Berger and Frank Porell. 2008. The Association Between Low Vision and Function. *Journal of Aging and Health* 20, 5: 504–525. <https://doi.org/10.1177/0898264308317534>
7. Hugh Beyer and Karen Holtzblatt. 1997. *Contextual Design: Defining Customer-centered Systems*. Retrieved April 12, 2018 from https://books.google.com/books?hl=en&lr=&id=JxQaQgOONGIC&oi=fnd&pg=PP2&dq=Beyer+1997-contextual+design:~defining+customer-centered+systems&ots=-TWZrI4Zv3&sig=S_ZCAU2YZc8k4ZtWRKb5jiHGYYo
8. Sarah A Bibby, Erin R Maslin, Roberta McIlraith, and Grace P Soong. 2007. Vision and self-reported mobility performance in patients with low vision. *Clinical and Experimental Optometry* 90, 2: 115–123. <https://doi.org/10.1111/j.1444-0938.2007.00120.x>
9. Alex Black, Jan E Lovie- Kitchin, Russell L Woods, Nicole Arnold, John Byrnes, and Jane Murrish. 1997. Mobility performance with retinitis pigmentosa. *Clinical and Experimental Optometry* 80, 1: 1–12. <https://doi.org/10.1111/J.1444-0938.1997.TB04841.X>
10. Jeffrey R. Blum, Mathieu Bouchard, and Jeremy R. Cooperstock. 2011. What’s around me? Spatialized audio augmented reality for blind users with a smartphone. In *International Conference on Mobile and Ubiquitous Systems: Computing, Networking, and Services.*, 49–62. https://doi.org/10.1007/978-3-642-30973-1_5
11. Rebecca Q. Ivers BOptom, Robert G. Cumming, Paul Mitchell, and Karin Attebo. 1998. Visual Impairment and Falls in Older Adults: The Blue Mountains Eye Study. *Journal of the American Geriatrics Society* 46, 1: 58–64. <https://doi.org/10.1111/j.1532-5415.1998.tb01014.x>
12. M. Bouzit, A. Chaibi, K. J. De Laurentis, and C. Mavroidis. 2004. Tactile feedback navigation handle for the visually impaired. In *IMECE2004*, 1–7. <https://doi.org/10.1115/IMECE2004-60450>
13. Megan Campbell, Cynthia Bennett, Caitlin Bonnar, and Alan Borning. 2014. Where’s My Bus Stop? Supporting Independence of Blind Transit Riders with StopInfo. *ASSETS ’14 Proceedings of the 16th international ACM SIGACCESS conference on Computers & accessibility*: 11–18. <https://doi.org/10.1145/2661334.2661378>
14. Kathy Y. Cao and Samuel N. Markowitz. 2014. Residual stereopsis in age-related macular degeneration patients and its impact on vision-related abilities: A pilot study. *Journal of Optometry* 7, 2: 100–105. <https://doi.org/10.1016/J.OPTOM.2013.12.003>
15. CDC. 2004. Summary Health Statistics for the U.S. Population: National Health Interview Survey, 2004. Retrieved May 3, 2015 from http://www.cdc.gov/nchs/data/series/sr_10/sr10_229.pdf
16. Verena R Cimarolli, Kathrin Boerner, Mark Brennan-Ing, Joann P Reinhardt, and Amy Horowitz. 2012. Challenges faced by older adults with vision loss: a qualitative study with implications for rehabilitation. *Clinical Rehabilitation* 26, 8: 748–757. <https://doi.org/10.1177/0269215511429162>
17. A Cox, A Blaikie, C J MacEwen, D Jones, K Thompson, D Holding, T Sharma, S Miller, S Dobson, and R Sanders. 2005. Visual impairment in elderly patients with hip fracture: causes and associations. *Eye (London, England)* 19, 6: 652–656. <https://doi.org/10.1038/sj.eye.6701610>
18. Steven R. Cummings, Michael C. Nevitt, Warren S. Browner, Katie Stone, Kathleen M. Fox, Kristine E. Ensrud, Jane Cauley, Dennis Black, and Thomas M. Vogt. 1995. Risk Factors for Hip Fracture in White Women. *New England Journal of Medicine* 332, 12: 767–774. <https://doi.org/10.1056/NEJM199503233321202>
19. D. Dakopoulos and N.G. Bourbakis. 2010. Wearable Obstacle Avoidance Electronic Travel Aids for Blind: A Survey. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)* 40, 1: 25–35. <https://doi.org/10.1109/TSMCC.2009.2021255>
20. Bradley E Dougherty, K Bradley Kehler, Richard Jamara, Nicole Patterson, Denise Valenti, and Fuensanta A Vera-Diaz. 2011. Abandonment of low-vision devices in an outpatient population. *Optometry and vision science : official publication of the American Academy of Optometry* 88, 11: 1283–7. <https://doi.org/10.1097/OPX.0b013e31822a61e7>

21. M R Everingham, B T Thomas, and T Troschianko. 1999. Head-mounted mobility aid for low vision using scene classification techniques. *International Journal of Virtual Reality* 3: 3–12.
22. David T Felson, Jennifer J Anderson, Marian T Hannan, Roy C Milton, Peter W.F. Wilson, and Douglas P Kiel. 1989. Impaired Vision and Hip Fracture: The Framingham Study. *Journal of the American Geriatrics Society* 37, 6: 495–500. <https://doi.org/10.1111/j.1532-5415.1989.tb05678.x>
23. Barney G. Glaser and Anselm L. Strauss. 1967. *The Discovery of Grounded Theory: Strategies for Qualitative Research*. Aldine Transaction, New York, NY.
24. R. G. & Golledge, J. R. & Marston, and C. M. Costanzo. 1997. Attitudes of Visually Impaired Persons Toward the Use of Public Transportation. *Journal of Visual Impairment & Blindness* 91, 5: 446–459. Retrieved April 14, 2018 from <https://escholarship.org/uc/item/34x1z4m8>
25. Kotaro Hara, Jon E. Froehlich, Shiri Azenkot, Megan Campbell, Cynthia L. Bennett, Vicki Le, Sean Pannella, Robert Moore, Kelly Minckler, and Rochelle H. Ng. 2015. Improving Public Transit Accessibility for Blind Riders by Crowdsourcing Bus Stop Landmark Locations with Google Street View: An Extended Analysis. *ACM Transactions on Accessible Computing* 6, 2: 1–23. <https://doi.org/10.1145/2717513>
26. R H Harwood. 2001. Visual problems and falls. *Age and Ageing* 30, SUPPL. 4: 13–18. https://doi.org/10.1093/ageing/30.suppl_4.13
27. R H Harwood, A J E Foss, F Osborn, R M Gregson, A Zaman, and T Masud. 2005. Falls and health status in elderly women following first eye cataract surgery: a randomised controlled trial. *The British journal of ophthalmology* 89, 1: 53–9. <https://doi.org/10.1136/bjo.2004.049478>
28. Stephen L. Hicks, Iain Wilson, Louwai Muhammed, John Worsfold, Susan M. Downes, and Christopher Kennard. 2013. A Depth-Based Head-Mounted Visual Display to Aid Navigation in Partially Sighted Individuals. *PLoS ONE* 8, 7: e67695. <https://doi.org/10.1371/journal.pone.0067695>
29. International Code Council. 2018. 2018 International Building Code. Retrieved April 16, 2018 from <https://codes.iccsafe.org/public/document/IBC2018>
30. William H. Ittelson. 1951. Size as a Cue to Distance: Static Localization. *The American Journal of Psychology* 64, 1: 54. <https://doi.org/10.2307/1418595>
31. J. T. Jobling, J. S. Mansfield, and G. E. Legge. 1997. Can motion parallax provide depth information for low-vision observers? *Investigative Ophthalmology and Visual Science* 38, 4.
32. Susan J. Leat and Jan E. Lovie-Kitchin. 2008. Visual Function, Visual Attention, and Mobility Performance in Low Vision. *Optometry and Vision Science* 85, 11: 1049–1056. <https://doi.org/10.1097/OPX.0b013e31818b949d>
33. G. E. Legge, D. Yu, C. S. Kallie, T. M. Bochsler, and R. Gage. 2010. Visual accessibility of ramps and steps. *Journal of Vision* 10, 11: 8–8. <https://doi.org/10.1167/10.11.8>
34. Gordon E. Legge, Paul J. Beckmann, Bosco S. Tjan, Gary Havey, Kevin Kramer, David Rolkosky, Rachel Gage, Muzi Chen, Sravan Puchakayala, and Aravindhan Rangarajan. 2013. Indoor Navigation by People with Visual Impairment Using a Digital Sign System. *PLoS ONE* 8, 10: e76783. <https://doi.org/10.1371/journal.pone.0076783>
35. Hong Liu, Jun Wang, Xiangdong Wang, and Yueliang Qian. 2015. iSee: obstacle detection and feedback system for the blind. *Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2015 ACM International Symposium on Wearable Computers - UbiComp '15*: 197–200. <https://doi.org/10.1145/2800835.2800917>
36. Jack M. Loomis, Reginald G. Golledge, and Roberta L. Klatzky. 1998. Navigation System for the Blind: Auditory Display Modes and Guidance. *Presence: Teleoperators and Virtual Environments* 7, 2: 193–203. <https://doi.org/10.1162/105474698565677>
37. Gang Luo and Eli Peli. 2006. Use of an Augmented-Vision Device for Visual Search by Patients with Tunnel Vision. *Investigative Ophthalmology and Visual Science* 47, 9: 4152–4159. <https://doi.org/10.1167/iov.05-1672>
38. Roberto Manduchi and Sri Kurniawan. 2011. Mobility-Related Accidents Experienced by People with Visual Impairment. *Insight: Research & Practice in Visual Impairment & Blindness* 4, 2: 44–54. Retrieved April 3, 2018 from <https://users.soe.ucsc.edu/~manduchi/papers/MobilityAccidents.pdf>
39. Sergio Mascetti, Dragan Ahmetovic, Andrea Gerino, and Cristian Bernareggi. 2016. ZebraRecognizer: Pedestrian crossing recognition for people with visual impairment or blindness. *Pattern Recognition* 60: 405–419. <https://doi.org/10.1016/J.PATCOG.2016.05.002>
40. Simon Meers and Koren Ward. 2005. A Substitute Vision System for Providing 3D Perception and GPS Navigation via Electro-Tactile Stimulation. *International Conference on Sensing Technology*, November: 551–556. Retrieved April 14, 2018 from

- <http://ro.uow.edu.au/infopapers/435>
41. P.B.L. Meijer. 1992. An experimental system for auditory image representations. *IEEE Transactions on Biomedical Engineering* 39, 2: 112–121. <https://doi.org/10.1109/10.121642>
 42. M. P. Menikdiwela, K.M.I.S. Dharmasena, and A.M. Harsha S. Abeykoon. 2013. Haptic based walking stick for visually impaired people. In *2013 International conference on Circuits, Controls and Communications (CCUBE)*, 1–6. <https://doi.org/10.1109/CCUBE.2013.6718549>
 43. Sue Mussatt, RN, and CLVT. 2014. Make Your Office Safer for Patients With Low Vision. *EyeNet Magazine*. Retrieved March 26, 2018 from <https://www.aao.org/eyenet/article/make-your-office-safer-patients-with-low-vision>
 44. Takanori Ōkoshi. 2012. *Three-dimensional imaging techniques*. Elsevier.
 45. Archana R Priyadarshini. 2024. Dual Objective Based Navigation Assistance to the Blind and Visually Impaired. *International Journal of Innovative Research in Computer and Communication Engineering* 2, 5: 4335–4342. Retrieved April 6, 2018 from www.ijirce.com
 46. Kristina Rand, Sarah Creem-Regehr, and William Thompson. 2015. Spatial Learning While Navigating With Severely Degraded Viewing: The Role of Attention and Mobility Monitoring. *J Exp Psychol Hum Percept Perform* 41, 3: 649–664. <https://doi.org/10.1037/xhp0000040>
 47. Joram J. van Rheede, Iain R. Wilson, Rose I. Qian, Susan M. Downes, Christopher Kennard, and Stephen L. Hicks. 2015. Improving Mobility Performance in Low Vision With a Distance-Based Representation of the Visual Scene. *Investigative Ophthalmology & Visual Science* 56, 8: 4802. <https://doi.org/10.1167/iovs.14-16311>
 48. J Saldaña. 2015. *The coding manual for qualitative researchers*. Retrieved April 12, 2018 from <https://books.google.com/books?hl=en&lr=&id=ZhxiCgAAQBAJ&oi=fnd&pg=PP1&dq=Saldaña,+J.+2015.+The+Coding+Manual+for+Qualitative+Researchers.+Sage,2015&ots=yITc5DMVcU&sig=M5xpoXYasFVBwDZDOrmZON99UIo>
 49. Kristen Shinohara and Jacob O. Wobbrock. 2011. In the shadow of misperception. In *Proceedings of the 2011 annual conference on Human factors in computing systems - CHI '11*, 705. <https://doi.org/10.1145/1978942.1979044>
 50. S. Shoval, J. Borenstein, and Y. Koren. 1994. Mobile robot obstacle avoidance in a computerized travel aid for the blind. In *Proceedings of the 1994 IEEE International Conference on Robotics and Automation*, 2023–2028. <https://doi.org/10.1109/ROBOT.1994.351166>
 51. Shruga Shoval, Iwan Ulrich, and Johann Borenstein. 2003. NavBelt and the GuideCane. *IEEE Robotics and Automation Magazine* 10, 1: 9–20. <https://doi.org/10.1109/MRA.2003.1191706>
 52. Vaibhav Singh, Rohan Paul, Dheeraj Mehra, Anuraag Gupta, Vasu Dev Sharma, Saumya Jain, Chinmay Agarwal, Ankush Garg, Sandeep Singh Gujral, M Balakrishnan, others, and A.G Fallis. 2010. “Smart”Cane for the Visually Impaired: Design and Controlled Field Testing of an Affordable Obstacle Detection System. *TRANSED 2010: 12th International Conference on Mobility and Transport for Elderly and Disabled Persons* 53, 9: 1689–1699. <https://doi.org/10.1017/CBO9781107415324.004>
 53. Sarit Szpiro, Shafeka Hashash, Yuhang Zhao, and Shiri Azenkot. 2016. How People with Low Vision Access Computing Devices: Understanding Challenges and Opportunities. In *Proceedings of the 18th International ACM SIGACCESS Conference on Computers and Accessibility - ASSETS' 16*, 171–180.
 54. Sarit Szpiro, Yuhang Zhao, and Shiri Azenkot. 2016. Finding a store, searching for a product: a study of daily challenges of low vision people. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing - UbiComp '16*, 61–72. <https://doi.org/10.1145/2971648.2971723>
 55. Victoria L. Tseng, Fei Yu, Flora Lum, and Anne L. Coleman. 2012. Risk of Fractures Following Cataract Surgery in Medicare Beneficiaries. *JAMA* 308, 5: 493–501. <https://doi.org/10.1001/jama.2012.9014>
 56. I. Ulrich and J. Borenstein. 2001. The GuideCane-applying mobile robot technologies to assist the visually impaired. *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans* 31, 2: 131–136. <https://doi.org/10.1109/3468.911370>
 57. Pablo Vera, Daniel Zenteno, and Joaquín Salas. 2014. A smartphone-based virtual white cane. *Pattern Analysis and Applications* 17, 3: 623–632. <https://doi.org/10.1007/s10044-013-0328-8>
 58. VisionAware. Low Vision and the White Cane: A Tool for Fall Prevention. Retrieved April 16, 2018 from <http://www.visionaware.org/info/essential-skills-2/an-introduction-to-orientation-and-mobility-skills/low-vision-and-the-white-cane-a-tool-for-fall-prevention/235>
 59. VisionAware. What Are Low Vision Optical Devices? Retrieved September 24, 2015 from <http://www.visionaware.org/info/your-eye-condition/eye-health/overview-of-low-vision->

devices/low-vision-optical-devices/1245

60. M Helmy Abd Wahab, Aa Talib, and Ha Kadir. 2011. Smart Cane: Assistive Cane for Visually-impaired People. *IJCSI International Journal of Computer Science Issues* 8, 4: 21–27. <https://doi.org/10.1145/2513383.2513449>
61. Wei Wen and Siamak Khatibi. Exploring and Measuring Presence of 3D Effect in a Classical Painting. Retrieved April 9, 2018 from <https://pdfs.semanticscholar.org/18ca/4c7bc465a8dc6b903ee6a571f62423297217.pdf>
62. Catherine G. West, Ginny Gildengorin, Gunilla Haegerstrom-Portnoy, Marilyn E. Schneek, Lori Lott, and John A. Brabyn. 2002. Is Vision Function Related to Physical Functional Ability in Older Adults? *Journal of the American Geriatrics Society* 50, 1: 136–145. <https://doi.org/10.1046/j.1532-5415.2002.50019.x>
63. Michele A. Williams, Caroline Galbraith, Shaun K. Kane, and Amy Hurst. 2014. “Just let the cane hit it”: how the blind and sighted see navigation differently. In *Proceedings of the 16th international ACM SIGACCESS conference on Computers & accessibility - ASSETS '14*, 217–224. <https://doi.org/10.1145/2661334.2661380>
64. Michele A. Williams, Amy Hurst, and Shaun K. Kane. 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 - ASSETS '15*: p28. <https://doi.org/10.1145/2513383.2513449>
65. Yuhang Zhao, Sarit Szpiro, and Shiri Azenkot. 2015. ForeSee : A Customizable Head-Mounted Vision Enhancement System for People with Low Vision. *ASSETS '15 The 17th International ACM SIGACCESS Conference on Computers and Accessibility*: 239–249. <https://doi.org/10.1145/2700648.2809865>
66. Yuhang Zhao, Sarit Szpiro, Jonathan Knighten, and Shiri Azenkot. 2016. CueSee: exploring visual cues for people with low vision to facilitate a visual search task. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing - UbiComp '16*, 73–84. <https://doi.org/10.1145/2971648.2971730>
67. Michael Zöllner, Stephan Huber, Hans Christian Jetter, and Harald Reiterer. 2011. NAVI - A proof-of-concept of a mobile navigational aid for visually impaired based on the microsoft kinect. In *IFIP Conference on Human-Computer Interaction*, 584–587. https://doi.org/10.1007/978-3-642-23768-3_88
68. Annuska Zolyomi, Anushree Shukla, and Jaime Snyder. 2017. Technology-Mediated Sight : A Case Study of Early Adopters of a Low Vision Assistive Technology. In *Proceedings of the 19th International ACM SIGACCESS Conference on Computers and Accessibility - ASSETS '17*, 220–229.