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Evaluation of an Accessible, Real-Time, and Infrastructure-Free Indoor Navigation System by Users Who Are Blind in the Mall of America

Nicholas A. Giudice[1,2], William E. Whalen[2], Timothy H. Riehle[3], Shane M. Anderson[3], and Stacy A. Doore[2]

Abstract

Introduction: This article describes an evaluation of MagNav, a speech-based, infrastructure-free indoor navigation system. The research was conducted in the Mall of America, the largest shopping mall in the United States, to empirically investigate the impact of memory load on route-guidance performance. **Method:** Twelve participants who are blind and 12 age-matched sighted controls participated in the study. Comparisons are made for route-guidance performance between use of updated, real-time route instructions (system-aided condition) and a system-unaided (memory-based condition) where the same instructions were only provided in advance of route travel. The sighted controls (who navigated under typical visual perception but used the system for route guidance) represent a best case comparison benchmark with the blind participants who used the system. **Results:** Results across all three test measures provide compelling behavioral evidence that blind navigators receiving real-time verbal information from the MagNav system performed route travel faster (navigation time), more accurately (fewer errors in reaching the destination), and more confidently (fewer requests for bystander assistance) compared to conditions where the same route information was only available to them in advance of travel. In addition, no statistically reliable differences were observed for any measure in the system-aided conditions between the blind

[1] Spatial Informatics Program, School of Computing and Information Science, The University of Maine, Orono, ME, USA
[2] Virtual Environment and Multimodal Interaction (VEMI) Laboratory, The University of Maine, Orono, ME, USA
[3] Koronis Biomedical Technologies, Minneapolis, MN, USA

Corresponding author:
Nicholas A. Giudice, PhD, Spatial Informatics Program, School of Computing and Information Science, The University of Maine, 348 Boardman Hall, Orono, ME 04469, USA.
Email: nicholas.giudice@maine.edu

and sighted participants. Posttest survey results corroborate the empirical findings, further supporting the efficacy of the MagNav system. **Discussion:** This research provides compelling quantitative and qualitative evidence showing the utility of an infrastructure-free, low-memory demand navigation system for supporting route guidance through complex indoor environments and supports the theory that functionally equivalent navigation performance is possible when access to real-time environmental information is available, irrespective of visual status. **Implications for designers and practitioners:** Findings provide insight for the importance of developers of accessible navigation systems to employ interfaces that minimize memory demands.

Keywords
indoor navigation system, blind travel, nonvisual navigation, speech-based interfaces

We have all experienced the frustration of being lost when trying to navigate to a desired location within a complex building. These situations not only result in wasted time, but they can also lead to undue stress and anxiety. For sighted travelers, however, consulting "you-are-here" maps and informational signs will eventually help them reach their destination. Indeed, there are a host of navigational supports and building conventions that can be of help (e.g., stores have prominent names, offices have numbers, exits and stairwells are marked with consistent signage, and building maps are often posted at key locations). Since the vast majority of these "spatial supports" are visual in nature, indoor navigation can pose a particular challenge for people who are visually impaired (i.e., those who are blind or have low vision). Braille signage represents one nonvisual exception, but these aids have limited utility, since they (1) are often difficult to locate without vision and (2) do not convey any directional or configurational cues.

This problem is largely solved for outdoor travel because of the availability of accessible GPS-based navigation systems in experimental projects (Loomis, Marston, Golledge, & Klatzky, 2005; Marston, Loomis, Klatzky, & Golledge, 2007) and commercially available systems focusing primarily on outdoor navigation, such as the Seeing-Eye GPS, made by Sendero Group; Blind Square, developed by MIPsoft; and Nearby Explorer, created by American Printing House for the Blind. Unfortunately, analogous indoor positioning with standard GPS receivers is neither accurate nor reliable, since satellite signals do not effectively penetrate large office buildings (Hightower & Borriello, 2001). Although there is a strong commercial push to solve this problem (see Coleman, Rajabifard, & Kolodziej, 2016, for review), indoor navigation systems are still in the development phase, and there are only two commercially available accessible solutions: the previoulsy mentioned Blind Square app and the ClickAndGo Wayfinding app developed by ClickAndGo Wayfinding Maps, LLC. These systems are still being refined, and only ClickAndGo Navigation provides actual route descriptions.

Technological solutions for indoor navigation

Despite the perspective advanced by most accessible navigation projects that indoor supports of this nature would be extremely beneficial to blind navigators, large-scale adoption and implementation of indoor navigation solutions (accessible or otherwise) is still far from a reality. We argue that a technological solution, whether for people who are blind or sighted, will require the development of current approaches on three interrelated fronts: indoor positioning, digital maps, and user interface.

Indoor positioning

In contrast to the global deployment of satellites supporting outdoor GPS-based positioning, indoor localization occurs on a per building basis, which means that creation of a robust network of indoor navigation assistance that is functionally equivalent to GPS-based localization will quickly become prohibitively expensive given the size and number of public buildings that would need to be retrofit. The same is true for most existing navigation solutions, since their positioning sensors and technologies need to be installed and maintained in the environment, which means that there are both initial capital costs and continued maintenance expenses associated with the deployment and operation of these systems (but see Apostolopoulos, Fallah, Folmer, & Bekris, 2014; Guerrero, Vasquez, & Ochoa, 2012). To address this issue, the MagNav system evaluated here adopts an innovative, infrastructure-free localization approach that makes use of the unique magnetic signatures from the building's steel structure to determine the user's position in the environment (see Method section).

Digital maps

Determining and structuring the data to be included in the digital building map is important for linking the user's real-time position to a particular location in the environment and for using this information to support tasks such as route generation and guidance (Gu, Lo, & Niemegeers, 2009). The challenge here is that the primary creators of large-scale commercial indoor mapping projects, such as Apple and Google, are using information content and data structures that may not be optimized for travelers with visual impairments. For instance, commercial systems may reference color or other visual attributes or landmarks for orientation and guidance, while also providing no nonvisual information about environmental cues that are used for supporting travel by people who are blind—for example, floor texture (tiled or carpeted), material properties of the walls (brick or wood), and auditory or olfactory information serving as off-route landmarks (Golledge, Klatsky, Loomis, Speigle, & Tietz, 1998; Legge, Downey, Giudice, & Tjan, 2016). Solving this problem involves two components: (1) use of a standardized data model that incorporates many sources of environmental information (including nonvisual cues) and (2) determining an accurate and efficient method of populating and updating the database with this information. Success here requires going beyond standard visual mapping practices to include theoretical knowledge of the perceptual and cognitive factors involved in information processing by visually impaired people and practical knowledge about orientation and mobility (O&M) training. As is described in the next paragraphs, MagNav was designed with both of these expertise domains in mind.

User interface

A successful indoor navigation system must convey information from the underlying digital map in an intuitive and usable manner. To support the greatest number of users, this interface should adopt universal design principles that employ multiple modes of information access that include visual, speech, spatialized audio, and haptic or vibration cues. The MagNav system evaluated here used a completely auditory interface providing verbal instructions and landmark information based on a host of environmental cues that are salient to nonvisual perception, that support orientation and route guidance for people with visual impairments, and that are taught to travelers with visual impairments during O&M training (Long & Giudice, 2010). Some examples of our multimodal instructions include “turn right when you feel the round cement pillar,” “turn left when you hear the fountain,” and “stop when you feel carpet under foot.” The messages were designed to be *spatially determinant,* meaning that each instruction provided unambiguous information about environmental relations or action states, which is important when crafting effective verbal descriptions (Mani & Johnson-Laird, 1982; Talmy, 1983). The descriptions used here were derived from a series of studies that manipulated the content and order of verbal messaging supporting nonvisual navigation (Giudice, 2004; Giudice, Bakdash, & Legge, 2007). Based on the optimal information content and structure established by that body of work, we adopted the following description logic with MagNav: action to take, distance to travel or angle to turn, and reference landmark or choice point indicating the end of the current instructional step (e.g., “walk 50 ft until you reach a brick wall”).

The environment chosen for testing in this study is also novel, since most research that has investigated accessible indoor navigation is conducted in highly controlled lab settings or experimental environments that were designed to facilitate the study. By contrast, the current research was carried out in the Mall of America (MOA) in Bloomington, MN, which is the largest retail and entertainment destination in the United States (see Figure 1). This large venue is certainly one that would benefit from navigational assistance, since it consists of 5.6 million square feet of indoor space, houses over 520 retail stores, and hosts over 40 million visitors per year (MOA, 2017).

Experimental evaluation

The goal of this study was to investigate the effectiveness and usability of MagNav for supporting nonvisual route navigation through a complex indoor environment with minimal intervention by the user. Other projects employing indoor positioning and accessible interfaces include systems using ultra-wideband (UWB) positioning (Martinez-Sala, Losilla, Sánchez-Aarnoutse, & García-Haro, 2015), a combination of UWB and GPS triangulation (Riehle, Lichter, & Giudice, 2008), an infrared camera to detect retroreflective barcodes during route finding (Legge, Beckmann, Tjan, Havey, & Kramer, 2013), inertial sensors in a smartphone (Apostolopoulos et al., 2014), combined inertial and infrared sensing (Guerrero et al., 2012), low-cost radio-frequency identification (RFID) tags (Ganz et al., 2012), a combination of RFID tags and GPS positioning (Hub & Schmitz, 2009), inertial sensing coupled with a smart phone’s camera (Coughlan & Manduchi, 2009), and digital location beacons (Cheraghi, Namboodiri, & Walker, 2017). However, all of these projects (but for Legge & colleagues, 2013) were designed as technology evaluations to assess whether or not the system supported a desired task. They were not conducted to provide empirical evidence in support of a theory, the experimental designs used did not employ any sort of control condition or make performance comparisons between different user groups, and rarely were formal inferential statistics used to analyze the data. The current research, while also serving as a user evaluation of the MagNav system, differs from these studies in that it is first and foremost a theoretically motivated, empirically validated study based on a true experimental design.

The main difference between using a navigation system to travel an unfamiliar route compared to a set of route instructions (e.g., those that may be given when asking directions from a passerby) is that the former provides real-time, context-sensitive messages about what the user is passing or actions to take at decision points along the route. By contrast, the latter is based on "up-front" instructions that require memory to match the verbal directions received with what is being perceived during route navigation. The implicit assumption is that real-time instructions are beneficial because they do not require a user to remember the route directions. However, beyond anecdotal evidence and the pilot work by Riehle and colleagues that this article extends, this is the first study to our knowledge that has carefully controlled the information content between the use of real-time and memory-based verbal instructions in order to investigate whether updated messages from a navigation system are truly beneficial. For a valid comparison, it is critical that the real-time updated verbal information matches that given in advance of route travel, meaning that the only difference between conditions is in the nature of memory load, not in the key information content of the verbal descriptions.

To address this issue, our blind participants traveled unfamiliar routes through MOA using either (1) real-time verbal instructions from MagNav that gave updated guidance as they walked the route (system-aided condition) or (2) by hearing the same instructions from the system as a static route description from the beginning of the route, thereby requiring accurate memory recall to correctly reach the destination (system-unaided condition). We hypothesized that access to real-time route-guidance information from MagNav would reliably improve the speed (route completion time), accuracy (correct localization of the route destination), and confidence (number of requests for assistance) for blind navigators compared to the same measures using information-matched, static route instructions.

Our second comparison of interest was between performance by the participants who are blind in the system-aided condition against a group of sighted control participants who used the system for guidance while also having visual access to the environment. This control is important, since it sets an upper bound of speed and accuracy with MagNav that, if matched by the blind group, would suggest optimal efficiency of the system (at least for route guidance). We hypothesized that access to real-time, system-aided information would confer similar advantages, irrespective of visual status, resulting in statistically indistinguishable performance between the blind and sighted participant groups. Such null results would not only lend additional evidence of system efficacy but would also provide empirical support for our theory that most challenges related to blind navigation abilities are due to insufficient access to navigation-critical information rather than to vision loss (Giudice, 2018).

Method

Participants

Twelve blind participants (six female, aged between 20 and 59 years, with total blindness or light perception) were evaluated. Four used our inertial-based magnetic system (Riehle et al., 2012) and eight used the system with inertial and step-based calibration (Riehle, Anderson, Lichter, Whalen, & Giudice, 2013). Although the underlying positioning technology differed slightly

Table 1. Blind participant information and demographics.

Sex	Age	Etiology of Blindness	Residual Vision	Age of Onset	Years Stable
Male	35	Leber's congenital amaurosis	Light perception	Birth	35
Female	39	Congenital glaucoma	None	Birth	39
Male	52	Retinitis pigmentosa	None	Birth	22
Female	59	Retinitis pigmentosa	None	8	35
Male	22	Bilateral Retinoblastoma	Light perception	1	10
Male	49	Optic demyelination with cortical damage	Light perception	11	38
Female	53	Fever	Light and minimal shape perception	Birth	Gradual deterioration
Female	39	Bilateral Retinoblastoma	None	1	38
Male	47	Optic demyelination with cortical damage	Light perception	11	36
Male	20	Bilateral Retinoblastoma	None	1	19
Female	37	Congenital glaucoma	None	1	36
Male	20	Bilateral Retinoblastoma	Light perception	1	10

between systems, the localization accuracy (estimated as $\sim$1 m), underlying building map, and interface and system operation were functionally identical. All 12 participants followed the same experimental procedures, used the same speech-based interface, and were evaluated on the same test metrics. All were highly confident travelers (averaging 4.8 days per week of independent travel outside of their home) and all had received 20 or more hours of O&M training (see Table 1 for information about the blind participants). None had ever previously used an indoor navigation system. Twelve age-matched sighted participants (five female and seven male) served as experimental controls. This project was approved by University of Maine's local ethics committee, and informed consent was obtained from all participants.

Environments and apparatus

Each experiment used five routes (one practice and four experimental) that were magnetically mapped and verbally annotated throughout the first floor of the MOA (Figure 2). The routes ranged from 645 to 805 ft in length and had between five and eight decision points (e.g., 45° or 90° turns).

Real-time positioning was performed by first walking through MOA with a magnetometer to detect and process the magnetic information that is integral to the steel frame structures of all large buildings. Once mapped and entered into an updatable building-specific database providing a lookup table of *X*-*Y*-*Z* coordinates, these location-specific magnetic signatures could then be associated with any desired information registered at this location (e.g., store names, descriptions of key choice points along the route, and salient environmental features). Thus, although the mapping occurs in advance of system use, as is also the case for GPS-based systems, once the indoor database is constructed, user tracking through the environment and the association of their location to the verbal labels in the map is done in real time during route travel using low-cost, body-worn inertial sensors (e.g., three-axis magnetometers, microelectromechanical system (MEMS) or MEMS accelerometers, gyroscopes, and pedometry sensors) to update user position based on their movement. Movement information was relayed in real time via Bluetooth to a smartphone containing the building database, navigation algorithm, and logging facilities (Figure 3). The verbal descriptions were wirelessly transmitted to a Bluetooth single-ear headset worn by the user (thereby not masking other ambient sounds that might be used during navigation). The true utility of this approach is that it allows the MagNav system to support indoor localization without any expensive infrastructure modifications beyond the initial mapping of the building's magnetic signatures. Details on technical development of the system and its preliminary testing can be found in two papers by Riehle, Anderson, Lichter, Whalen, and Giudice (2013) and Riehle and colleagues (2012).

Design and procedure

A mixed-model design was used with the blind participant group representing a within-subjects factor and the sighted control group representing a between-subjects comparison. During practice, participants were familiarized with the system and asked to walk a practice route in both the aided and unaided condition (none demonstrated any difficulty with the task). During the route navigation phase, participants were positioned at the start of one of the four predetermined experimental routes and were instructed to use the verbal descriptions to follow the route to its destination. Navigation was blocked into two conditions (aided and unaided), each with two routes (condition order was counterbalanced between participants). Participants were requested to walk at their typical pace and to stay close to the wall (i.e., shorelining).

In the "system-aided" condition, participants received real-time, updated assistance from MagNav as they walked, describing what actions to take, indicating stores being passed, alerting them to salient landmarks on the route, length of each route segment, and describing decision points (e.g., route instructions). Information about the start of the next route segment (e.g., an upcoming turn) was announced approximately 15 ft in advance. This lead time allowed participants to use their mobility skills to detect the decision point, while also accommodating for any positional "noise" introduced by error accumulation from the inertial tracking module.

In the unaided memory condition, the same verbal instructions were given by the system (but for the store names, which pilot studies found to impose an undue cognitive load). However, instead of being triggered along the route, the full set of route instructions was heard as a single description from the device at the route's origin. As such, the aided and unaided conditions used the same interface and were based on identical information content about the route. Because of their static nature, however, the unaided trials differed from the system-aided condition as accurate route completion required the user to memorize, mentally rehearse, and spatially update the front-loaded verbal instructions and to match this memorized information with the cues perceived during travel. This condition is similar to the best case scenario for what a person with visual impairment might receive during typical travel with no orientation device (i.e., if they were to ask for route directions from a knowledgeable bystander).

Participants in both conditions used their desired mobility device to detect and avoid any obstructions during navigation (dog users: eight, cane users: four). An experimenter always followed behind the participant to guard against any undetected obstacles. The experimenter also acted as a "bystander" who could answer questions if the participant needed additional assistance or became disoriented. This information was similar to what might be requested or given from a random passerby during typical independent travel. The information provided in a bystander request included repeating the current route step instruction and reorienting the participant to the route if necessary. The route destination was indicated by the system (aided conditions) or by the participant (unaided memory conditions). Bystander requests about the next decision point were not provided on the last route step, since this information would give away the route destination. Upon completing the navigation phase, all blind participants filled out a survey to gauge their satisfaction with the system. The sighted participants, representing a control group in terms of speed and accuracy, walked the same routes with the system to guide them using their typical vision (aided condition). Since they did not a priori know the route destination, they needed to follow the system's verbal instructions to correctly reach the route terminus.

Results and discussion

Log files for 3 of the 72 total route trials were corrupted, and these data were replaced based on mean substitution of the group means for the relevant condition before analysis. Analyzing the route navigation data allowed us to compare performance on overall travel time, destination localization accuracy, and the number of bystander requests as within-subjects factors for the system-aided versus the system-unaided conditions and as between-subjects factors for comparing blind versus sighted participant groups. The results provide compelling support for the efficacy of using real-time information from the MagNav system for navigating highly complex indoor environments (see Table 2).

Bystander requests

The bystander requests' measure provides a metric of user confidence and a gauge of memory load effects during travel based on the number of times participants made requests for assistance. In the system-unaided condition, 11 of the 12 blind participants made bystander requests across 19 of the 24 route trials, representing a total of 46 requests, averaging 3.8 requests per person, which means that when no real-time route information was available, 92% of the blind participants needed assistance on 79% of the routes traveled. By comparison, only four total bystander requests were made by 4 of the 12 participants in the system-aided condition across the 24 route trials. In other words, when real-time information was available, 75% of the participants traveled the routes with no additional assistance beyond what the system provided, and when requests were made, they only occurred on 17% of the routes traveled, with 0.33 mean requests made per person. Paired-sample *t*-tests comparing the aided versus unaided bystander requests confirmed that performance reliably differed between conditions, $t(23) = 4.91$, $p < .05$, $d = 0.70$. A total of three bystander requests were made across the 24 trials by 2 of the 12 sighted control participants (averaging 0.25 per person), representing around 13% of the routes traveled.

Table 2. Descriptive statistics for blind and sighted participants: bystander requests, route completion time, and route completion accuracy.

	Blind								Sighted			
	Unaided				Aided				Aided			
Variables	*M*	*SD*	*SE*	*n*	*M*	*SD*	*SE*	*n*	*M*	*SD*	*SE*	*n*
Bystander requests (per person)	3.80	2.51	0.726	12	0.33	0.492	0.142	12	0.25	0.62	0.17	12
Route completion time (seconds)	290	111.24	22.70	24	212	54.54	11.13	24	208	37.59	6.67	24
Route completion accuracy (% completion)	0.25	0.4423	0.0902	24	1.00	0	0	24	1.00	0	0	24

Note. SD = standard deviation; *SE* = standard error.

Independent-sample *t*-tests verified that this small numeric difference did not reliably differ between blind and sighted users in system-aided conditions, $t(20.90) = 0.36, p > .05, d = 0.16$. However, an independent-sample *t*-test, adjusted for homogeneity of variance, showed highly significant differences between the number of requests made in the blind unaided condition versus the sighted aided condition, $t(25.92) = 4.68, p < .05, d = 1.35$.

These results clearly demonstrate that when real-time route information was provided, participants' need for external assistance was almost completely eliminated. Indeed, the requests that were generated by both blind and sighted participants in the system-aided conditions were primarily due to confusion imposed by system lag in triggering the messages at the appropriate place. It is likely that such requests would be reduced to zero as system accuracy is improved with future refinements. The results from the unaided condition also demonstrate that increasing memory load during navigation leads to a reliable decrease in people's confidence of where they are, as evidenced by the dramatic increase of bystander requests in this condition.

Route completion time

Comparing the amount of time needed to navigate the routes between the system-aided and system-unaided conditions and user groups also yielded marked differences. Blind participants using the system took 78 s less time to complete the routes than the same group using static, memory-based descriptions, with a paired-sample *t*-test demonstrating that aided performance (averaging 212 s) was significantly faster than unaided performance (averaging 290 s), $t(23) = 3.45, p < .05, d = 0.70$. By contrast, there was only a negligible 4-s difference observed between the blind system–aided group and the sighted system–aided control group, with an independent-sample *t*-test showing no reliable difference between the 212 s and 208 s route traversal times, respectively, $t(46) = 0.35, p > .05, d = 0.10$. Of note, independent-sample *t*-tests, adjusted for homogeneity of variance, revealed that performance by the sighted control group was reliably better than that of the blind participants in the system-unaided memory condition, 208 s versus 290 s, respectively, $t(28.19) = 3.43, p < .05, d = 0.99$. We interpret these findings as providing compelling

Table 3. Postexperiment survey questions from 12 blind participants.

Participant	Q1: Use of the system made route navigation easier than navigating without assistance	Q2: Use of the system improved your confidence of successfully reaching the goal	Q3: Use of the system did not add much useful information beyond the up-front verbal descriptions	Q4: You would be more likely to travel independently to unfamiliar buildings if you had an indoor navigation system to provide route guidance	Q5: You often experience anxiety or concerns about traveling to large unfamiliar buildings	Q6: Access to an indoor navigation system that provided real-time route information would likely not change your frequency of traveling to new places	Q7: You would be satisfied with having access to route information before travel and don't think having real-time information from an indoor navigation system is necessary
P01	1	1	7	1	2	7	7
P02	1	1	7	1	6	6	5
P03	1	1	7	1	1	5	7
P04	1	1	5	1	1	6	7
P05	1	1	6	1	2	6	6
P06	1	1	7	1	1	5	7
P07	1	2	7	1	2	7	6
P08	1	2	6	2	2	6	6
P09	2	4	6	1	7	5	7
P10	1	2	3	1	3	5	6
P11	1	2	5	1	2	5	6
P12	1	3	6	1	3	6	7
Means	1.083333333	1.75	6	1.083333333	2.666666667	5.75	6.416666667

Note. Seven-point Likert-type scale (1 = *strongly agree*, 4 = *neutral*, and 7 = *strongly disagree*).

Figure 1. Mall of America rotunda view courtesy of Explore Minnesota: July 2017.

empirical evidence that blind travelers using real-time route information from our system can perform on par with sighted travelers, whereas traditional memory-based, off-line methods of information gathering (e.g., receiving verbal route instructions in advance of travel) result in significantly slower performance by people who are blind compared to sighted controls (or blind participants using the navigation system).

Route completion accuracy

Not surprisingly, route completion performance in the system-aided conditions for blind participants and sighted controls was perfect (100%), since the system "told" navigators when they had reached the destination. By contrast, performance by the blind group was markedly worse in the unaided memory condition, where they only correctly found the destination on 6 of the 24 trials. This finding means that when route information was only available from memory recall, rather than being provided in real-time during navigation, participants failed to correctly execute the entire route on 75% of the trials. In addition, of the six correctly executed routes, 50% required assistance along the way (representing six bystander requests), meaning that only 12.5% of the routes were correctly executed based solely on memory of the verbal route information provided before travel. These findings demonstrate the value of real-time information delivery during navigation and suggest that reliance on memory from off-line verbal descriptions is not sufficient for accurate and efficient performance, even for seasoned blind travelers, as were tested here.

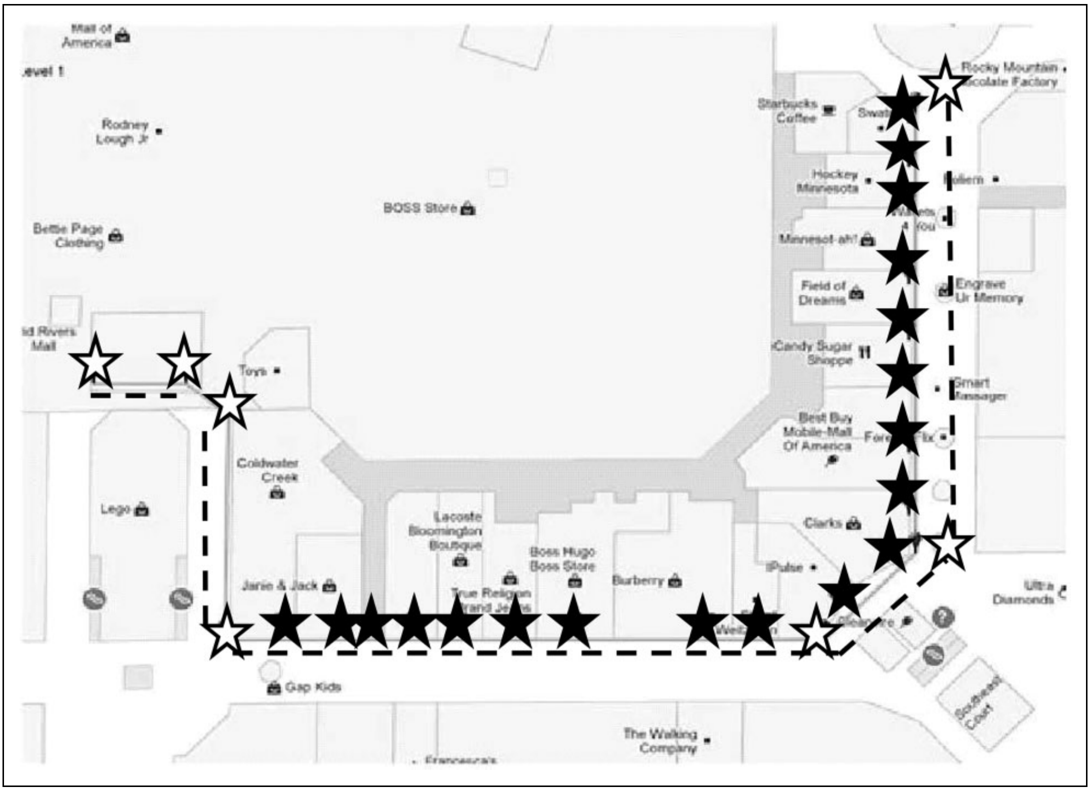

Figure 2. An experimental route at the Mall of America, overlaid on the Google Map for the Mall. Black hollow stars outline the straight-line segments; solid black stars show the location of points of interest. *Source*: Reprinted with permission from Riehle, Anderson, Lichter, Whalen, and Giudice (2013; ©IEEE 2013).

Posttest survey results

The posttest survey results provide qualitative evidence that corroborate the empirical data and indicate several clear preferences associated with using the navigation system (see Table 3). Based on a 7-point Likert-type scale (1 = *strongly agree*, 4 = *neutral*, and 7 = *strongly disagree*), all of the blind participants indicated a strong preference for use of the MagNav system versus up-front instructions. For instance, the average score of 1.1 from the 12 blind participants on Question (Q) 1 and the average rating of 6.4 on Q7 clearly demonstrate that people want more than traditional static, memory-intensive descriptions. Furthermore, the 1.1 on Q4 and 1.8 on Q2 indicate that, at least based on future projections from these self-reports, people would not only travel more frequently with access to a system such as MagNav, but that they would be more confident and less stressed in doing so. These are important results given estimates that 30% of blind people do not travel independently outside of their house (Clark-Carter, Heyes, & Howarth, 1986).

Conclusions and applications

This article investigated the efficacy of using dynamically updated, context-sensitive verbal descriptions for supporting route guidance through indoor environments using

Figure 3. Navigator application running on a Nexus 4 smartphone, showing users current position estimate. *Source*: Reprinted with permission from Riehle, Anderson, Lichter, Whalen, and Giudice (2013; ©IEEE 2013).

MagNav, an accessible navigation system. The research led to several definitive outcomes. First, the quantitative results across all three test measures provide compelling behavioral evidence that blind navigators receiving real-time verbal information from the MagNav system performed route travel faster (navigation time), more accurately (fewer errors in reaching the destination), and more confidently (fewer requests for bystander assistance) compared to conditions where the same route information was only available in advance of travel. These results demonstrate the cognitive cost imposed by requiring memory recall during navigation and speak to the importance for developers to employ interfaces that minimize memory demands (e.g., our system-aided condition). The empirical results are well-aligned with the qualitative survey data showing that people often experience anxiety when navigating in large, unfamiliar buildings, but that use of our system improved their confidence, made route travel much easier, and increased the likelihood of future independent travel (see Table 2). Although the current results are congruent with previous evaluations of accessible indoor navigation systems (Apostolopoulos et al., 2014; Cheraghi et al., 2017; Ganz et al., 2012), they extend this body of work in two important ways. First, rather than the traditional approach of conducting a simple system evaluation, our findings were based on a well-controlled experiment investigating the role of memory load on navigation performance by matching the verbal route information provided while manipulating the manner that it was delivered (e.g., real-time system-aided vs. memory-based system-unaided conditions). Second, in contrast to most results in this domain, which are obtained in constrained experimental settings, our findings have high ecological validity (i.e., apply to realistic situations), since testing occurred in the MOA, representing one of the largest indoor environments in the world, and was performed during typical business hours, with no isolation of the participants from other mall patrons. We believe that this lack of isolation was an important aspect of our experiment, since MOA is particularly challenging for blind travelers because of its irregular structure, heavy pedestrian traffic, significant ambient noise, and broad, undefined thoroughfares with numerous obstacles and few accessibility features. Such "testing in the wild" is a core tenet of human-centered design, which argues that the true efficacy of a product cannot be evaluated without first testing the intended demographic in a realistic environment or situation

(Shneiderman, Plaisant, & Jacobs, 2009). Unfortunately, with few exceptions (see Crandall, Brabyn, Bentzen, & Myers, 1999), this step is often ignored during the research and development phase of information-access technologies, meaning that the functional utility of most products is never evaluated in "difficult" environments where travelers who are visually impaired would most benefit from its use.

Another contribution of this work relates to our theoretical understanding of the role of information access on spatial behaviors between blind and sighted navigators. Where performance by the blind group in the unaided memory-based conditions was reliably worse than performance of the sighted controls across all of the dependent factors, performance across all measures in the system-aided conditions was almost identical between the blind and sighted participants. This outcome demonstrates that when sufficient nonvisual environmental information is available to travelers with visual impairments, their performance is not only on par but statistically indistinguishable from their sighted counterparts. These results contribute to the growing body of evidence showing functionally equivalent spatial behaviors between visually impaired and sighted participants when appropriate information is provided (see Loomis, Klatzky, & Giudice, 2013, for review). Our results are interpreted as corroborating the view that most navigation challenges faced by visually impaired individuals are not due to deficits stemming from vision loss but to a lack of information-access tools and technologies supporting accurate spatial perception, environmental learning, and spatial problem-solving (Giudice, 2018).

In sum, the convergence of statistically validated performance measures and self-reported participant enthusiasm for MagNav demonstrates the value of providing real-time route guidance and supports the efficacy of our system as a promising accessible solution for indoor navigation. The key advantage of the MagNav system over other wayfinding solutions is that it is infrastructure free and built on commercial hardware, meaning that the investment cost for deployment is nominal. Developing solutions to solve the vexing challenge of indoor navigation is more than a convenience; safe and accurate travel through large buildings is a critical component of one's independence and quality of life. When this is not possible (or perceived as an undue burden), many blind people simply do not travel on their own or pursue important opportunities (Clark-Carter et al., 1986; Marston & Golledge, 2003). These concerns, and the associated constraints they impose on navigational behaviors, certainly contribute to troubling statistics—for example, the near 70% unemployment and underemployment rate of working-age adults with visual impairments (Chua & Mitchell, 2004; Kaye, Kang, & LaPlante, 2000), that only 11% of visually impaired adults have a bachelor's degree (Erickson, Lee, & von Schrader, 2012), and the significantly higher than typical social isolation experienced by this demographic (Nyman, Gosney, & Victor, 2010). These issues are exacerbated by challenges to independent navigation but could be dramatically improved through development of better navigational supports; the MagNav system evaluated here representing just one such solution.

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