Use of an Indoor Navigation System by Sighted and Blind Travelers: Performance Similarities across Visual Status and Age

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11

This article first reviews the pros and cons of current accessible indoor navigation systems and then describes a study using commercial smart devices to navigate routes through a complex building. Our interest was in comparing performance when using real-time narrative descriptions (system-aided condition) vs. a memory-based condition where the same narrative information was only provided to users from the route's origin. We tested two groups of blind and visually impaired (BVI) users, including people above and below 60 years of age, as well as a third sighted control group. Evaluating older BVI participants is important, as the majority of vision loss is age-related, yet navigation performance using access technology is rarely studied with this demographic. Behavioral results demonstrated that access to real-time (system-aided) information led to better navigation accuracy and greater confidence by blind users compared to the information-matched memory condition. Performance for blind participants over 60 years old was nearly identical with their younger peers—an important outcome supporting the efficacy of using navigational technologies by this fast-growing population. Route completion accuracy and requests for assistance did not reliably differ between blind and sighted participants when using the system, suggesting that access to narrative route information led to functionally equivalent navigation behavior, irrespective of visual status. Survey results revealed strong user support for real-time information and provided important guidance for future interface refinements.

NIH grant Phase II SBIR: R44EY021412-02 and NSF grant: IIS-1822800 supported technical development of the system and funded this research.
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1936-7228/2020/08-ART11 $15.00
https://doi.org/10.1145/3407191

CCS Concepts: • **Human-centered computing** → *Empirical studies in accessibility*; **Accessibility technologies**; *Accessibility design and evaluation methods*; **Sound-based input/output**;

Additional Key Words and Phrases: Narrative route descriptions, Bluetooth location beacons, indoor navigation, blind/visually impaired navigation, older adult navigation

ACM Reference format:
Nicholas A. Giudice, Benjamin A. Guenther, Toni M. Kaplan, Shane M. Anderson, Robert J. Knuesel, and Joseph F. Cioffi. 2020. Use of an Indoor Navigation System by Sighted and Blind Travelers: Performance Similarities across Visual Status and Age. *ACM Trans. Access. Comput.* 13, 3, Article 11 (August 2020), 27 pages.
https://doi.org/10.1145/3407191

1 INTRODUCTION

The reason that indoor navigation is often more challenging than traveling outdoors is partly due to technical limitations, as GPS-based positioning is unreliable within large buildings [1]. Although various technologies have been tested for supporting indoor localization (see Reference [2] for review), none have yet emerged as a widespread and widely used standard analogous to GPS-based outdoor navigation. Beyond technical limitations, the indoor navigation challenge is exacerbated by the nature of indoor spaces, as buildings are usually multi-level 3D structures with limited naming conventions for the walkable regions or addressing schemes of specific locations, i.e., the street names and building addresses that support outdoor travel [3]. As a consequence, it is more difficult to accurately represent the building structure on a real-time navigation map or to provide turn-by-turn verbal route instructions, as is available with outdoor navigation systems. These differences frequently make indoor navigation, especially when finding routes through large buildings, more frustrating and error-prone [4–6].

To help mitigate these indoor navigation challenges, architects and building developers utilize a host of aids to assist indoor wayfinding, such as maps, signs, directional arrows, alpha-numeric room labels, and color-coded cues for distinguishing different spatial regions. Most of these tools for self-orientation and localization are visual in nature. As a result, anybody navigating in large, complex buildings is at a particular disadvantage if they cannot visually access this key wayfinding information, as is the case for blind or visually impaired (BVI) travelers or in situations when vision is not available (e.g., the power goes out, emergency response scenarios, etc.).

This is a well-known problem and the quest for a viable solution has motivated an active research community studying technological approaches to support nonvisual indoor navigation, primarily for use by BVI travelers.

Rather than focusing on technical development, our emphasis here was on investigating how use of the navigation system impacted behavioral performance. Several human factors and user interface (UI) parameters were addressed in the study, including: perception vs. memory-based information access, participant age, visual status, and collaborative navigation techniques. Results from route navigation performance (quantitative evaluation) and system usability evaluations (qualitative feedback) demonstrated that people perform best when they have access to real-time (perceptual) guidance from a navigation system and that this benefit is similarly manifested for both older and younger BVI participants and between sighted and blind users. In the remainder of this article, we (1) provide a background of accessible indoor navigation systems, (2) give an overview of the system we used to support the study, (3) discuss the relevance of our variables of interest with respect to probing how (and for whom) accessible navigation systems are generally used, (4) describe an *in situ* study carried out in a large university building using our system, and (5) couch the findings in terms of how they relate to existing research with navigation systems and how the current data could be used to provide guidance and best practices for improving future research in this domain.

2 BACKGROUND AND RELEVANT RESEARCH

2.1 Navigation Assistance Technologies

As of the writing of this article, there are only a few commercially available accessible solutions that incorporate some level of real-time speech-based indoor navigation assistance, e.g., the ClickAndGo wayfinding app, the BlindSquare navigation app, the NavCog navigation app, and the Clew AR-based app [7–10]. However, these systems are still being refined and the indoor positioning is imprecise. Most of the experimental indoor navigation systems that have been tested have proven extremely effective in supporting indoor route guidance and spatial learning with BVI participants (or blindfolded-sighted users). These accessible systems generally employ a speech-based user interface and have used a range of localization technologies. Accurate nonvisual route navigation through complex commercial buildings has been shown with systems using ultra-wideband (UWB) positioning [11, 12], an infrared camera to detect retro-reflective barcodes [13], a smartphone's inertial sensors [14], RFID tags [15], and inertial dead-reckoning techniques coupled with infrared sensing [16]. Magnetic sensing from the building's steel infrastructure has also been used to provide localization [17] as has computer vision techniques using a smartphone's camera to detect colored markers [18] or barcodes [19]. Recently, there has been increased interest in the use of low-energy Bluetooth beacons for positioning, given their low per-unit cost and ease of beacon placement in key environmental locations. Promising results with systems using this technology have been shown in studies evaluating route guidance performance through a shopping mall [20], a mall and hotel [21], a train station [22], and complex university buildings [23–25]. In aggregate, research with these systems has been extremely positive with respect to their efficacy in supporting travel of unfamiliar indoor routes without vision. However, despite their many benefits, there is still no clear single solution for solving the vexing indoor navigation challenge for BVI travelers.

Another factor that is rarely considered relates to whether this technology will work for supporting navigation by older adults. This is an important question, given that the vast majority of vision loss is age-related, with the greatest prevalence in people over 65 years of age [26, 27]. Indeed, the incidence of people with significant visual impairment is expected to double between 2010 and 2030 owing to the aging of the population [28]. Despite these demographic trends, none of the projects on indoor navigation systems for BVI users (discussed above) included an older cohort. Although the European-based MOBIC initiative incorporated older BVI adults as part of the research, the focus was on outdoor navigation [29]. Several studies have specifically addressed indoor navigation systems for older BVI adults but their emphasis has been on describing technical system development, with Reference [30] not including a formal user evaluation and Reference [31] only using blindfolded-sighted older adults. The current study included an older adult BVI group, with interest in comparing their behavioral performance with and without the navigation system against a younger BVI cohort (see Section 4.2).

2.2 Effect of Human Factors on Verbal Navigation Assistance

Establishing the format for the narrative route descriptions was an important starting point when designing our user interface, as the connection between space and language has long been a vexing issue to researchers and developers. While most accessible navigation systems employ some form of synthesized speech output in their UI, the rationale for the verbal messages used is rarely described. One study that formally investigated route instructions by BVI navigators emphasized the importance of providing verbal route guidance rules, clear descriptions of guidance functions, and a consistent linguistic format [32]. However, this research only addressed outdoor travel, and while the functional recommendations are relevant to all navigation systems, the very different naming conventions and physical structure of indoor spaces limits specific applicability for use with indoor route instructions. Although research exists on the information requirements needed to support nonvisual spatial learning and its relation to the development of effective navigation technologies [33, 34], there is a dearth of research on specifying the best structure or information content to be used in navigational messaging, especially supporting indoor travel without vision. Some insight can be gleaned from studies looking at verbal information used by BVI people in route directions, although this work was based on uncontrolled naturalistic usage, e.g., what was described in email exchanges [35] or focused on differences in information content used between sighted and BVI navigators [36]. What is clear from a synthesis of this literature is that BVI travelers rely on different types of environmental cues in their route descriptions than sighted navigators, emphasizing relative language specifying distance and direction, specifying cues about alternative routes or if a destination was missed, relying on context-dependent landmarks vs. global/structural cues (especially for orienting during indoor travel), using more sensory cues and motion-dependent information, and preferring meaningful spatial chunks in the route descriptions (e.g., "walk 4 blocks").

Beyond the presence or absence of sight, the crux of the challenge of verbally mediated navigation is that language is not intrinsically spatial. Whereas vision and touch, the so-called "spatial senses," afford direct perceptual access to geometric relations in the environment, language specifies spatial relations indirectly, necessitating cognitive mediation based on a set of formal symbols and rules. To reduce cognitive load and avoid error-prone behavior, effective verbal instructions must be designed to be spatially determinant, e.g., they must convey clear and unambiguous information about environmental relations or actions to take [37–39]. Using consistent terminology and adopting a set of rules for verbally conveying spatial information (i.e., fixed order and syntax of information presentation) is particularly important for supporting nonvisual spatial behaviors [40, 41]. Consistency of messaging also ensures continuity between all descriptions and helps the user to parse the verbal message and to direct their attention to the information they find most useful when navigating [42].

3 SYSTEM OVERVIEW

3.1 Technical Overview

As with most of the previous work on accessible indoor navigation systems, the system used here employed a smart device as the core computational platform and speech messages as the principal output. We used commercial Apple devices (iPhones/iPods) to deliver the speech-based narrative descriptions rather than Android devices, as over 80% of BVI cell phone users are estimated to be using the iOS-based ecosystem [43]. This design decision was meant to ensure that the form factor, gesture logic, and understanding of the UI in our system was already familiar and intuitive to our participants.

The underlying database supporting the narrative route descriptions was developed using a commercial platform from ClickAndGo Wayfinding Maps LLC (www.clickandgomaps.com). Use of the ClickAndGo platform allowed us to enter data about the routes, landmarks, and environmental features into the system in a consistent manner that has already been optimized for commercial implementation. Beyond use of an established indoor data model, the key advantage of this platform is that the narrative (speech-based) route guidance information provided by the system is designed from the onset by blindness and mobility professionals to incorporate environmental cues and route information that is most beneficial to supporting BVI travelers. Some examples from the descriptions used here included mentioning surface changes under foot such as wood or carpet, salient material properties such as a brick or cement wall at a key choice point, and auditory/olfactory information to indicate landmarks. Even if large commercial initiatives (such as Indoor Google Maps, Apple Venue maps, and OpenStreetMaps), as reviewed in Reference [44] succeed in mapping all public buildings, these services are unlikely to include such nonvisual cues in their underlying digital maps and spatial databases. This is problematic for BVI travelers, as it is precisely these types of auditory, olfactory, and tangible environmental cues that are taught to support safe and efficient navigation without vision by orientation and mobility (O&M) instructors [45].

Real-time localization with the system was done through the combination of low-cost, low-energy Bluetooth proximity beacons by Estimote (http://estimote.com/) and by the human user, acting as a "sensor" [46], meaning that they could update position by coupling the step-by-step narrative route instructions received from the system with their own location-specific perception (see Section 4.4 for details).

3.2 Narrative Descriptions

The structure and content of the route instructions adopted here were partly determined by the narrative descriptions found to be most beneficial by the O&M professionals involved with the Click and Go narrative mapping service and partly based on the most accurate results from our prior work that manipulated the content and order of verbal messaging supporting "wayfinding with words" (as elaborated in References [42, 47]). These results guided our current instruction set, where participants heard information following the sequence: action to take, ⇨ Distance/metric information, ⇨ landmark/destination information (i.e., "Walk 60 feet to a set of closed fire doors."). Metric/distance information was always followed by a salient landmark. This description logic is also consistent with previous research on verbal transitions between indoor and outdoor spaces, which advocated describing both the user action and the immediate environment relevant to that action [48]. Our explicit use of landmarks (or reference points) in each route instruction is generally considered good practice, as their presence helps to reduce errors and increase navigator confidence [49]. They also aid in the consolidation of route directions into accurate cognitive maps [50], which is particularly important for BVI travelers [51].

4 RESEARCH QUESTIONS AND CONTRIBUTIONS

The current study was designed to experimentally evaluate several research questions (RQs) relating to the user interface and performance of accessible indoor navigation systems. Our emphasis builds on the trend in the accessible indoor navigation literature on studying user performance data for quantifying when and where errors occur [52–54]. The contributions of this research are relevant to providing guidance on UI design considerations for implementation in future navigation systems, as well as adding to our theoretical understanding of how nonvisual route information is used to support spatial behaviors across a range of users.

4.1 RQ1: Does Navigation Performance Differ as a Function of Perceptually Based vs. Memory-based Information Access?

This question speaks to an important yet poorly studied issue related to when route information is available during navigation. Traveling a route when using a navigation system vs. without assistance usually involves the same goals and behaviors, with the principal difference being the added route guidance instructions afforded by the former. However, for a blind traveler, the same environmental information that is readily perceived through vision along the route by sighted people is often slower, less precise, and more error-prone to access and use as stable/reliable landmarks via nonvisual sensing [55, 56]. Researchers studying blind navigation have argued for decades that use of these spatially imprecise, nonvisual environmental cues lead to greater reliance on cognitive processes and computationally intensive moment-to-moment spatial problem-solving, resulting in navigation by BVI individuals as being more mentally effortful and cognitively taxing compared to the same tasks performed with perceptually driven visual guidance [57–59]. While navigation systems assist this process, it is unclear whether BVI spatial performance is facilitated by the mere presence of accessible environmental descriptions and guidance information or if the spatial context of that information availability is what makes a difference. For instance, it is common practice for a BVI traveler to obtain verbal instructions about an environment to be visited or a route to be subsequently followed from a friend, family member, random passerby, or their O&M instructor. What is unknown is whether execution of this information from memory is as accurate and efficient as receiving the same information from a real-time navigation system. We postulate that access to route information provided beforehand (i.e., out of context) would lead to significantly worse navigation performance compared to availability of the same information *in situ*. The rationale being that instructions available during real-time navigation (1) reduce the cognitive load associated with memorization and (2) provide a means of validating the inherent imprecision of nonvisual perception, e.g., hearing that the hallway widens and being told from the system that there is an elevator lobby. To address this issue, we experimentally compared two navigation conditions. In the real-time, perception-based condition, the narrative route information was available to the user from the system during route navigation. In the static, memory-based condition, the same (information-matched) narrative descriptions were provided but they were only available at the beginning of the route. Thus, the only key difference between these two conditions is in how the information is provided: with route execution in the perceptual condition, participants could match the information provided by the system at each route step with what they directly perceived from nonvisual sensing in the surrounding environment as they walked. By contrast, the memory-based condition required participants to listen to, and accurately learn, the complete route description before they started walking (similar to directions given by a knowledgeable bystander). Accurate performance required them to match the front-loaded route instructions from memory with what was perceived along the route (i.e., the standard practice for supporting unaided indoor travel without vision).

We predicted that BVI performance with the real-time, perceptual condition would lead to reliably faster, more accurate, and more confident route travel than performance in the static, memory-reliant condition. While this outcome has intuitive appeal, surprisingly, it is poorly studied in the literature. Indeed, as discussed more in Section 4.4, there is evidence to the contrary suggesting that use of real-time navigation systems can sometimes hurt performance [60]. The results of this comparison contribute theoretical insight about the role of context-sensitive interfaces for reducing working memory demands/cognitive load, with outcomes also providing empirical validation for the continued time, effort, and expense of developing real-time speech-based indoor navigation systems.

4.2 RQ2: Does BVI Navigation Performance Differ as a Function of Participant Age?

The answer to this question contributes to our understanding of the effects of age-related cognitive load on navigation performance without vision and whether the benefits of accessing real-time navigational assistance predicted in RQ1 manifest equivalently for younger and older BVI participants. *Although there is a dearth of research addressing BVI spatial performance and aging,* empirical research with older sighted adults has suggested age-related performance deficits are frequently observed for allocentric spatial tasks, e.g., cognitive map development after learning both real and virtual indoor environments [61–64], but egocentric spatial tasks, such as those used in route following or finding locations on a map, are often preserved in older adults [65, 66]. Age-related spatial deficits in working memory, especially when under load, have also been shown with older sighted adults (see Reference [67] for review). The only study to our knowledge that specifically investigated the conjunction of indoor navigation, aging, and visual impairment did not find any interaction of these factors on navigation performance [68]. Kalia and her colleagues also demonstrated that the presence of non-geometric cues, such as the landmarks described in the route descriptions used here, were particularly beneficial to older BVI navigators [68]. However, learning in this study was done in a virtual environment, and testing in the corresponding physical environment was purely memory-based. The current work is the first study to our knowledge comparing *in situ* indoor route-finding performance between older and younger BVI participants, with and without use of a navigation aid. Based on the findings from the sparse navigation literature with BVI older adults and given that our route navigation task involves use of egocentric cues, we predict no statistically reliable differences between BVI older and younger groups for the real-time system-aided conditions. However, differences are likely to manifest as a function of age in the memory condition, owing to its increased working memory demands.

4.3 RQ3: Does Navigation Performance using the Real-time System Differ as a Function of Visual Status?

In this study, sighted participants served as a control group, which is often missing in assistive technology research. Their inclusion here was to set an upper performance limit with use of the same real-time narrative instructions from the system as were available to BVI navigators. We expected that the sighted controls would yield the best overall performance (lowest number of errors, requests for assistance, and fastest route traversal times), as they had access to the greatest amount of information during route travel. Following from this logic, BVI participants, who have access to less information availability from nonvisual sensing, may exhibit worse performance compared to their sighted peers. However, we predicted that no significant performance differences would be observed between BVI and sighted groups during system-aided navigation in this study. The rationale for this prediction being that (1) the narrative descriptions were designed to convey all the necessary information needed to support the route navigation task (i.e., eliminate the information gap between sighted and BVI participants) and (2) that the availability of real-time information would reduce the cognitive load for BVI travelers associated with matching route guidance information with the standard nonvisual sensory cues used to support navigation without vision.

4.4 RQ4: Can the User Effectively Collaborate with the System to Support Route Navigation?

This question relates to our design decision for the navigation system to not be fully automatized. This approach contrasts with the traditional model, where the narrative information is automatically spoken as the user progresses along the route, e.g., the turn-by-turn auditory directions provided by most GPS-based outdoor navigation systems or the accessible indoor navigation systems discussed earlier (but see Reference [46]). While one may intuitively conclude that it is always better to reduce user involvement with the system by providing dynamically updated information, this automation is not without problems. For instance, studies have clearly shown that failure to attend to the environment when simply following fully automated directions can lead to reliance on the system at the detriment of spatial attention and learning of global environmental relations [60, 69–71]. To our knowledge, this issue has never been formally studied with BVI users, but we posit that the environmental disengagement and divided attention caused by the "crutch" of technology could be particularly dangerous for BVI travelers, as they rely more heavily than their sighted peers on active awareness of proximal environmental information and use of cognitive resources to perform spatial problem-solving [55, 72]. To overcome this reliance on the technology, we adopted an approach that fostered a collaborative interaction style where participants actively engaged with the system to receive instructions as they navigated. With our interface, participants manually "walked" through the route instructions (i.e., flicked through the list of step-by-step messages on the phone interface) as they physically traversed the route (see methods). As such, the user acted as part of the system, serving as a functional sensor–matching system descriptions and beacon messages against what was perceived through direct environmental sensing as they traveled along the route. This interaction between user and system, based on sharing of the cognitive/technical load, is thought to promote situational awareness and by extension, navigational efficacy [53]. We postulated that this interactive exchange would benefit BVI navigators, as adoption of a user-controlled progression of route steps should (1) encourage engagement in the navigation process and (2) provide an interactive self-correction mechanism, as users can match their current perception with the narrative information to stay oriented on the route. This approach builds on similar techniques based on the "user as a sensor," which worked well in the seminal Navitar project, a nonvisual indoor route-guidance system where the user was involved in the localization process [46]. In that work, however, users were only required to "update" the system by identifying a few key decision points. The current system extends this collaborative involvement, as participants are kept in the information exchange loop for all route instructions, since they must actively match and update their nonvisual perceptions with the provided verbal information on every route step before advancing to the next step. In doing so, we hypothesized that this engaged process would not only improve overall route navigation performance compared to our memory condition but would do so in a way that reduces the known detrimental effects imposed by fully automated navigation systems.

We also included a pre-journey learning condition in this study, where BVI participants had advance access to some of the routes before participating in the experiment. This variable was motivated by findings in the literature suggesting that the ability to explore and learn a route or environment in advance of physically going there, whether through access to virtual environments [42, 73] or via tactile/audio-tactile maps [74, 75] is particularly beneficial to BVI navigators. We were interested in further studying the efficacy of this off-line learning given recent results showing that while use of a virtual pre-journey navigation app led to accurate unassisted real-world navigation, this benefit was not manifest when subsequent travel was done in conjunction with a navigation system [76]. These results suggest that the advantages of prior (remembered) spatial knowledge gained from pre-journey learning may be significantly reduced when participants have access to real-time *in situ* information from a navigation system (as we are using in this study). However, this pre-journey data was ultimately not included in the current article due to differential learning caused by variability in how much participants reviewed the routes ahead of time (e.g., some participants studied the route information only once, while others studied the information 10 or more times). We continue to believe in the importance of studying the value of pre-journey learning but emphasize the need for carefully controlling this factor during evaluation, i.e., by providing participants with an explicit learning protocol to follow in advance of the *in situ* trials. Our lack of this standardized guidance negates the value of this measure in the current study (note that elimination of this data did not impact interpretation of any other variables of interest).

5 METHOD

5.1 Participants

Fourteen blind participants (9 female), between the ages of 28 and 70 years, participated in this research (see Table 1). To maximize inclusiveness of our sample, we did not use age as a selection

Table 1. Descriptive Information for Blind Participants

Sex	Etiology of Blindness	Onset Age	Residual Vision	Age	Education	Mobility Aid	Ind. Nav. Days
F	Stargardt	10	Peripheral	70	G	Cane	7
F	Retrolental Fibroplasia	1	N	69	G	Dog	7
F	Congenital Cataracts	Birth	Blurry Objects	53	SC	Cane	7
F	Congenital Glaucoma	Birth	Light/Dark	28	SC	Cane	7
F	Retinitis Pigmentosa	1	Light/Dark	42	U	Cane	4
F	Meningitis	18	N	54	G	Dog	7
M	Toxoplasmosis	Birth	Very large print	40	U	Cane	7
F	Leber's Congenital Amaurosis	2	Light/Dark	62	G	Cane	6
M	Congenital Glaucoma	2	N	64	U	Cane	7
F	Retinitis Pigmentosa	2	Light/Dark	63	G	Cane	7
M	Retinitis Pigmentosa	5	Very large Print	34	HS	Cane	7
M	Retinitis Pigmentosa Inverse	3	N	68	U	Dog	7
M	Retinopathy of Prematurity	3	N	63	SC	Cane	7
F	Keratitis	18	Blurry Objects	42	U	Cane	6

parameter when recruiting participants, e.g., restrict participation to people under a certain age threshold, as is generally done in studies of ETAs to reduce known variability of the BVI population [55]. An unintended consequence of this decision was recruitment of a sample with an equal bimodal distribution of people below and above 60 years of age. This provided us with an excellent serendipitous opportunity to study the impact of age on performance as a key variable of interest in the current study. In support of this decision, 60 years of age is a common threshold for research studying spatial performance between younger and older participant groups, and the literature is clear that if normal age-related spatial deficits manifest, they usually occur in people over 60 years (for reviews, see References [67, 77]). The older adult group included seven BVI participants between 60 and 70 years of age ($M = 65.6$) and the younger group included seven BVI participants between the ages of 28 and 54 ($M = 41.9$). Our selection criteria, based on legally blind people who use a primary mobility aid during navigation (e.g., the long cane or dog guide), represent a functional classification argued as being most useful for spatial navigation studies [55]. Information was also recorded from BVI participants about O&M training and the type of cell phone used in daily life. All but one reported they had received 10 or more hours of O&M training, and all but one used an iPhone (the remaining person did not use a cell phone).

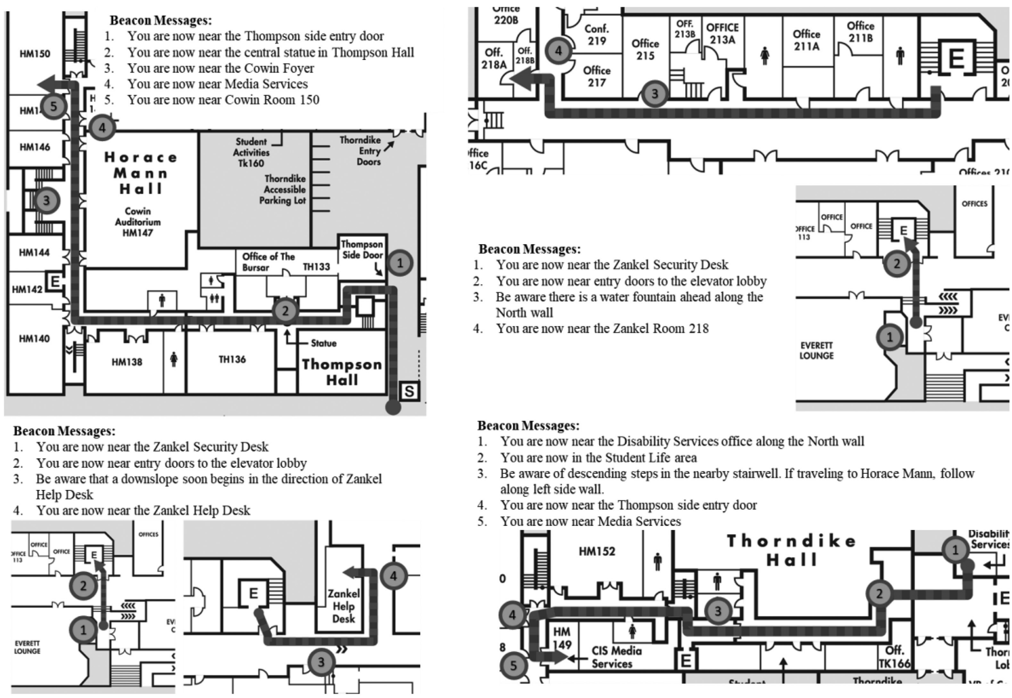

Fig. 1. The four experimental routes are illustrated, top left (route 2: 375 ft, 114.3 m), top right (route 4: 185 ft, 56.4 m), bottom left (route 3: 100 ft, 30.5 m), and bottom right (route 1: 225 ft, 68.6 m). The locations of the beacons are shown as numbered circles. The number in each circle refers to the corresponding beacon message. In each figure the starting point is indicated by the small circle at the end of the line nearest to beacon number 1. The end of each route is indicated by the arrow at the end of the line nearest to beacon(s) numbered 4 or 5.

In addition, seven sighted controls (two female), age 24–60 ($M = 34$), participated in the study. All participants were unfamiliar with the test environments. All gave informed consent and received monetary compensation for their participation.

5.2 Environments and Apparatus

Four experimental routes (and one additional practice route) were used through the Teachers College complex on the Columbia campus in New York City. The routes differed in their overall topology but were similar in complexity. Half of the test routes traversed two floors and required use of an elevator. The number of instructional steps ranged between 8 and 11, the number of decision points (any location with two or more allowable movement trajectories, not including reversals) ranged between 5 and 8, the number of digital Bluetooth beacons ranged between 4 and 5, and the approximate route length ranged from 100 to 370 feet (30.5 to 112.8 m; see Figure 1 for the experimental routes). Narrative descriptions of each route were compiled in advance and rendered using the ClickAndGo mapping platform (see Appendix A for full route descriptions). Participants used an iOS smart device, either an iPhone 5 or 5th generation iPod Touch, to receive narrative route information and location-specific beacon messages. Both devices had the same ~4-inch diagonal screen size (90.25 mm height × 51.60 mm width). Speech rate and volume were user-selectable. Sixteen Estimote low-energy Bluetooth Proximity Beacons (FCC ID: 2ABP2-EST0114) were installed along the four routes, each set to trigger an audio notification on the device within an approximate 15 ft (~4.6 m) detection bubble.

5.3 Procedure

A mixed model design was used: within-subjects factor = navigation mode (system-aided vs. memory-based), between-subjects factors = age (younger vs. older BVI participant groups), and visual status (BVI vs. sighted participant groups). The blind participant groups were exposed to four conditions, a system-aided route guidance condition and a memory-based route navigation condition in both normal and pre-journey learning modes (as described earlier, data from the two pre-journey learning conditions are not included here). The sighted control group ran in two separate route trials, performed only in the system-aided route guidance condition. The experiment was composed of three phases.

Phase 1: Practice. During practice, participants were familiarized with the narrative route descriptions, interface elements, beacon messages, and system interaction. After interface familiarization, they were given practice with the experimental procedure by walking a sample test route using the system. The practice session included corrective feedback and addressed all questions, with participants not moving on to the experimental trials until they felt comfortable with the information received and were able to accurately complete the route (none exhibited any confusion with the task or information presentation).

Phase 2: Route Navigation. During route navigation, participants were brought to the beginning of one of the four pre-defined routes and asked to navigate from its origin to its destination as quickly and accurately as possible (route by condition order was counterbalanced to avoid unintended learning/order effects).

System-aided condition: In this mode, participants accessed narrative descriptions from the system as they walked the routes. The narrative information was given in instructional steps (which can be conceptualized as route chunks) that described (1) salient landmarks encountered along the route, (2) any decision points (e.g., turns, doors, or any route elements that required a user to choose between two or more possible changes in trajectory), and (3) a description of the action to take at these decision points (e.g., turn x degrees right, go through the door, and continue ahead y feet, etc.). Each instructional step was given following a fixed description logic (see Section 3.2). Route instructions did not advance/update automatically as users walked along the route; instead, participants manually updated the narrative steps using gestures on the device's touchscreen as they walked, thereby matching the route information provided with their perception of the immediate surrounds to localize their position. Users could flick forward on the touchscreen to advance to the next route instruction, tap to repeat the current message, or flick back to reverbalize the previous route step. They also received real-time confirmation of salient landmarks and environmental features contained in the narrative description by digital Bluetooth beacons strategically positioned along the route, e.g., at the elevator lobby. Beacon messages were spoken automatically when the user walked within a pre-defined threshold radius of approximately 4.6 m. By design, the beacon messages were only meant as a secondary, redundant validation cue, they neither auto-advanced the instructional steps, nor were they densely populated along the route, as has been done in other beacon navigation studies [21, 23, 25]. Of note, the beacon information was salient from both visual and nonvisual perception, e.g., fire door, elevator, meaning that both BVI and sighted users could benefit from reinforcement of these landmarks.

Unaided Memory Condition: Participants in this mode walked the routes using the exact same narrative instructions as were provided in the system-aided condition but rather than accessing this information in real-time during *in situ* navigation, the instructions were provided all at once from a stationary position at the route's origin. Participants had up to five minutes to learn the narrative instructions, which they accessed in the same manner as the system-aided condition, e.g., flicking through the list of route steps on the device to progress from the start-point (at their current location) to its endpoint. While the context-sensitive beacon messages were not provided during route travel, the landmarks they referenced were provided within the up-front route instructions. Thus, while the same route instructions and environmental information was available from both conditions, route execution in the memory-based condition required accurate memorization, mental rehearsal, and spatial updating of the front-loaded verbal instructions and recall of this information to match with the environmental cues perceived during route travel to determine their position.

In both conditions, BVI participants used their normal mobility aid (long cane or dog guide) during travel to detect and avoid any obstructions (see Table 1 for details). An experimenter followed behind at all times to guard against collision with any undetected obstacles and to clarify any system messages. This experimenter also served as a "bystander" who could answer questions if the participant became disoriented or felt they needed additional assistance (similar to what might be requested from a random passerby during independent travel). A bystander request resulted in the experimenter repeating the route step corresponding to the participant's current position and reorienting them to the route if necessary. This procedure has worked well in previous research, as it mimics what might occur in normal situations when a BVI traveler asks for assistance, as well as allows us to gain important data on where confusion occurs during navigation [17]. A second experimenter also followed the participant to log their trajectory, correct for navigation errors, and to tally error counts and number of bystander requests. The route destination was indicated either by the system in the aided conditions or by participant self-report in the unaided memory conditions. If participants mislocalized the route's end, they were provided feedback by the experimenter until they reached the correct destination. After route completion, participants were brought to the origin of the next route and performed the same sequence of actions.

A group of sighted participants, serving as controls, also walked the routes under normal visual conditions while using the system to guide them along the route. As they did not know the destination ahead of time, they needed to follow the system's instructions to correctly reach the destination. Performance by these sighted controls provided a "best case scenario" for using the system in a temporally optimal manner, and their route traversal data was used as a comparison benchmark with that observed from the BVI participants.

Phase 3: Qualitative User Input. Upon completion of the route navigation phase, the BVI participants were given several survey instruments, incorporating both closed-ended questions and open-ended responses, to characterize the usability of the system, identify its strengths and weaknesses, determine perceived impacts on travel behaviors, and probe the likelihood of user adoption and perceived benefits if such a system were commercially available. This qualitative user data is extremely important, as it exposes aspects of the system that are simply not possible to elucidate from the empirical results.

5.4 Variables and Analyses

Three independent variables were compared in the study: (1) device usage mode (system-aided real-time information vs. system-unaided memory information), (2) BVI Participant age (BVI participants under 60 years vs. BVI participants over 60 years), and (3) visual status (blind vs. sighted participants). Our test measures were based on four dependent variables: (1) bystander requests, the number of instances that a participant requested experimenter assistance during navigation; (2) navigation errors, the number of errors made during route travel, defined as wrong turns, deviation of more than four steps from the correct route, or over/under-shooting of the destination;

(3) route completion accuracy, whether participants correctly found the end of the route without assistance; and (4) navigation time, the temporal duration required to navigate from the route's origin to its destination (or perceived destination). All statistical analyses were conducted using the R statistical package [78].

Data from the BVI participants on each dependent variable were first submitted to separate (system-aided vs. system-unaided) non-parametric tests for related samples, including the Wilcoxon signed rank test for the bystander requests, navigation errors, and navigation time data and a related-samples McNemar's Chi-Squared test for the route completion accuracy data. The effects of age group and visual status on BVI performance on both system-aided and unaided trials were analyzed using non-parametric tests for independent samples, with the bystander requests, navigation errors, and navigation time data submitted to Mann-Whitney-Wilcoxon rank sum tests and the route completion accuracy data submitted to a Pearson Chi-Squared test. Familywise error rates were controlled by adjusting reported p values using the Holm-Bonferroni procedure (this correction was performed separately for each dependent variable). To directly compare the system-aided performance of the sighted participants, who performed two trials, with the single trial of the BVI participants in each of the system-aided and system-unaided conditions, only the second trial from the sighted data was analyzed. In addition to matching the trial/group analyses, this procedure is congruent with our design motivation to include the sighted control group as representing a best-case scenario in terms of temporal and error performance.

6 RESULTS

6.1 Navigation Data

As predicted, the effect of device mode on route completion accuracy for BVI participants revealed greater accuracy during aided vs. unaided route navigation, $\chi^2(1) = 4.17$, $p = 0.041$. During unaided navigation, 64% of participants failed to correctly navigate to the end of the route. Eight (88%) of those 9 participants asked for assistance through one or more bystander requests. During aided navigation, only 21% of participants failed to complete the route. Of these 3 who did not complete the route, 1 asked for assistance through a bystander request. Of the 11 successful navigations, 9 (82%) participants did not seek assistance through bystander requests. None of the analyses comparing BVI performance across age groups or between BVI participants and sighted controls reached significance (see Table 2).

During route navigation, there was a statistically reliable effect of device mode as a function of the number of bystander requests made by BVI participants, $V = 28$, $Z = 2.30$, $r = 0.44$, $p = 0.021$ (see Figure 2 and Table 3). The median number of bystander requests (1.5) during unaided navigation was significantly greater than during aided navigation (0.0). As with the previous analyses, neither participant group nor age group comparisons revealed any statistically reliable differences on route completion accuracy (see Table 2).

The effect of device mode on the number of total navigation errors made by BVI participants did not reach significance, $V = 31$, $Z = 0.98$, $r = 0.19$, $p = 0.328$. For a detailed summary of these data, see Table 4. As with the bystander requests, comparison of navigation errors revealed no significant effects for age (BVI participants <60 years vs. BVI participants >60 years) or between participant group (BVI participants vs. sighted participants) (see Figure 3 and Table 3).

The time required to travel the route in its entirety revealed no statistically significant effects of device mode on navigation time, $V = 57$, $Z = 0.24$, $r = 0.05$, $p = 0.808$ (see Table 3). Additionally, neither participant group nor age group comparisons of navigation time revealed any significant effects (see Table 2).

Table 2. This Table Presents the Results of the Comparisons for Each Dependent Variable Between Age Group (BVI Adults > 60 Years vs. < 60 Years) and Visual Status (BVI vs. Sighted Participants)

	Route Completion Accuracy	*Bystander Requests*	*Navigation Errors*	*Navigation Time*
Age group for system-unaided trials	$\chi^2(1) = 0$, $p = 1$	$W = 24$, $Z = 0$, $r = 0$, $p = 1$	$W = 28.5$, $Z = 0.46$, $r = 0.12$, $p = 1$	$W = 32$, $Z = 0.87$, $r = 0.23$, $p = .495$
Age group for system-aided trials	$\chi^2(1) = 0$, $p = 1$	$W = 35$, $Z = 1.79$, $r = 0.48$, $p = .228$	$W = 29.5$, $Z = 0.64$, $r = 0.17$, $p = 1$	$W = 36$, $Z = 1.39$, $r = 0.37$, $p = .495$
Visual status for system-unaided trials	$X^2(1) = 5.47$, $p = .077$	$W = 72.5$, $Z = 1.90$, $r = 0.42$, $p = .228$	$W = 72.5$, $Z = 1.83$, $r = 0.40$, $p = .201$	$W = 67$, $Z = 1.31$, $r = 0.29$, $p = .495$
Visual status for system-aided trials	$\chi^2(1) = 0.44$, $p = 1$	$W = 51$, $Z = 0.16$, $r = 0.04$, $p = 1$	$W = 76.5$, $Z = 2.21$, $r = 0.48$, $p = .111$	$W = 79$, $Z = 2.24$, $r = 0.49$, $p = .100$

The reported p values were corrected using the Holm-Bonferroni procedure for each of the dependent variables.

Table 3. Table Denoting the Median and Range for Navigation Time, Navigation Errors, and Bystander Requests for BVI Aided, BVI Unaided, and Sighted Aided Conditions

	Navigation Time		Navigation Errors			Bystander Requests		
	Median	Range	Median	Range	Total	Median	Range	Total
BVI Unaided	279	111–628	1.0	0.0–6.0	23	1.5	0.0–7.0	30
BVI Aided	289	140–544	1.0	0.0–3.0	16	0.0	0.0–1.0	3
Sighted Aided	204	145–376	0.0	0.0–2.0	6	0.0	0.0–2.0	3

The sum of total navigation errors and bystander requests across participants is also presented.

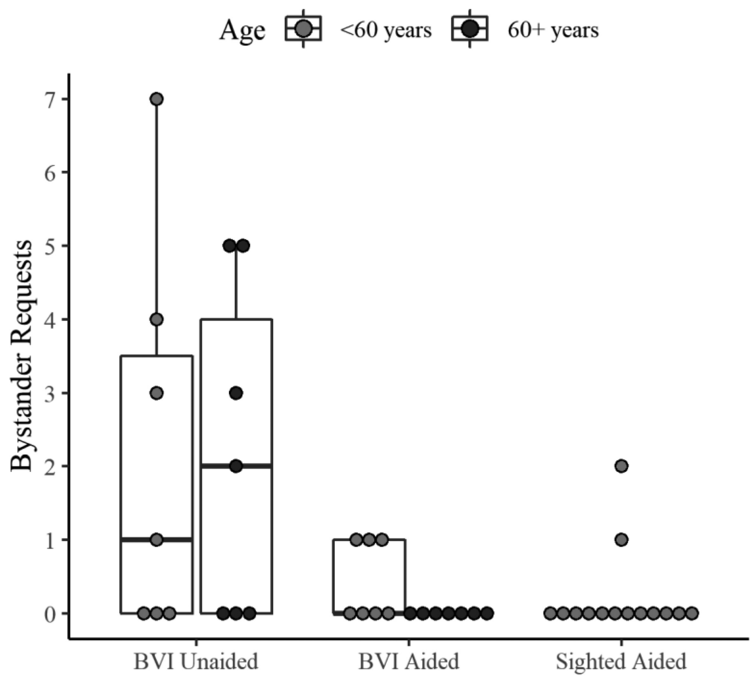

Fig. 2. Boxplot including individual datapoints for bystander requests separated by age group.

Table 4. Types of Errors Made by Both BVI and Sighted Participants

Error Type	BVI Unaided	BVI Aided	Sighted Aided
Made a wrong turn			
At an intersection	2	1	1
Within an open space	0	2	0
At a door/doorway	6	5	2
Walked past a decision point			
At an intersection	5	0	0
At a door or elevator	8	2	2
Error type not recorded	3	4	1

6.2 Qualitative Survey Data and User Input

After completing the experiment, the BVI participants were given a multi-part survey to evaluate the mental effort associated with the different conditions and to solicit their feedback, preferences, and opinions of using the device. This survey data also provided important qualitative evidence that corroborates the empirical data. Participants were first asked to rank order the four conditions (system-aided vs. unaided, with and without pre-journey learning) with respect to the mental effort required for each and the conditions they would most prefer to use. Note that we included the pre-learning survey data in this analysis, as user input provides important guidance on its utility, or lack thereof, for inclusion in future studies. The conditions were ordered separately for each measure from 1 to 4, with 1 indicating the least effort and most strongly preferred and 4

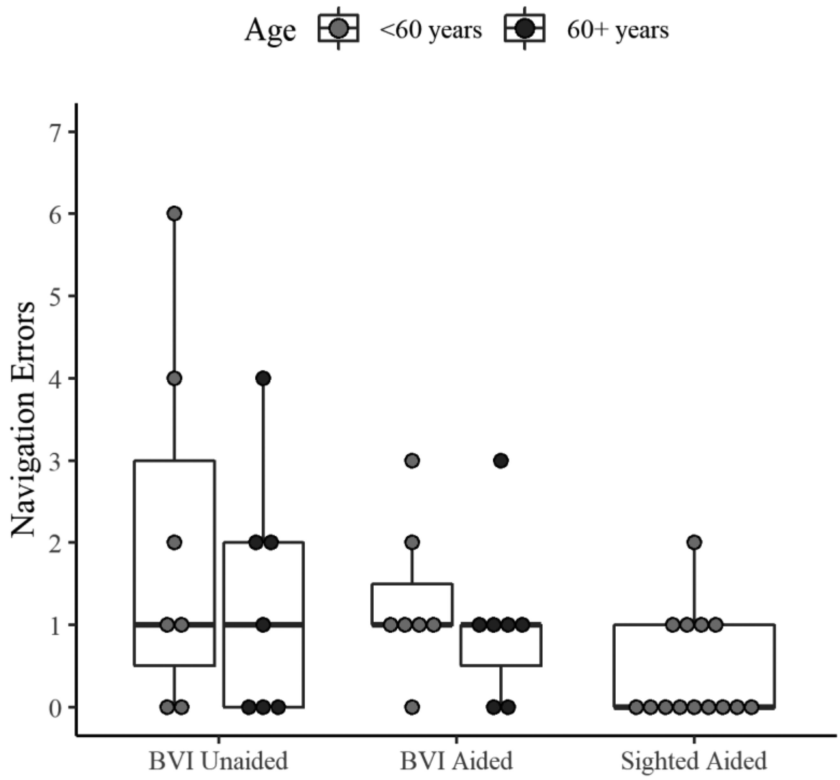

Fig. 3. Boxplot including individual datapoints for Navigation Errors separated by age group.

Table 5. This Table Provides Mean Responses (with Standard Deviation in Parentheses) for Two Ranked Measures from a Post-study Survey

	Pre-journey System-aided	System-aided	Pre-journey System-unaided	Unaided memory
Ease of Use	1.2 (0.4)	2.1 (0.8)	3.1 (0.7)	3.7 (0.5)
Preference	1.1 (0.3)	2.0 (0.4)	3.1 (0.5)	3.8 (0.4)

A value of 1 represents the easiest or most preferred condition and a value of 4 represents the hardest or least preferred condition.

indicating the most effort and least preferred. Twelve BVI participants completed this portion of the survey. These data clearly indicate that aided navigation was preferred to, and considered easier than, unaided navigation and that conditions involving pre-journey learning were considered more preferable and easier to use than conditions that did not include pre-journey learning. These rankings also indicate that system-aided conditions were preferred and easier to use regardless of pre-journey learning (see Table 5).

For targeted evaluation, six closed-ended questions (see Table 6) were asked using a seven-point Likert-Scale (1 - strongly disagree, 4 - neutral, and 7 - strongly agree). These data were submitted to individual One-sample Wilcoxon Signed Rank Tests (with continuity correction) comparing the response for each question to the neutral point (4) of the scale. Data are reported with p values adjusted using the Holm-Bonferroni procedure. Significant results indicate that the observed median was different from the hypothetical median (the neutral response of 4). Overall, the participants'

Table 6. The Six Targeted Survey Questions and Mean Responses from 14 Participants (Based on a 7-point Likert Scale)

	Question	Median
1	Use of the real-time location system made route navigation easier than navigating the routes without assistance	7*
2	Access to the pre-journey information made route navigation easier than navigating the routes without prior access	6*
3	Use of the real-time location-based system improved your confidence of successfully reaching the goal	6*
4	You would be more likely to travel independently to large unfamiliar buildings if you had an indoor navigation system to provide real-time guidance information	7*
5	You often experience anxiety or concerns about traveling to large unfamiliar buildings	4
6	You would be satisfied to have access to navigation information about a route before you travel and don't think having real-time information from an indoor navigation system is necessary	2*

Questions where the median response was significantly different from neutral (4) are indicated with an asterisk.

evaluations of the device were quite favorable, with user responses corroborating their empirical data. For instance, using the system during navigation was viewed as making route guidance significantly easier than relying on memory (question #1), $V = 55$, $Z = 2.86$, $r = 0.91$, $p = .024$, with access to the system also significantly improving user confidence in successfully reaching their goal (question #3), $V = 54$, $Z = 2.70$, $r = 0.85$, p .027. While the opportunity of pre-journey learning (question #2) was rated as reliably helping/improving navigation performance, $V = 45$, $Z = 2.63$, $r = 0.83$, $p = .027$, participants did not agree with the statement that pre-journey information alone is sufficient, i.e., access to real-time information from an indoor navigation system is not necessary (question #6), $V = 2$, $Z = -2.40$, $r = 0.76$, $p = .033$. Although participants were neutral about experiencing anxiety or concerns when traveling to large unfamiliar buildings (question #5), $V = 13$, $Z = -0.09$, $r = 0.03$, $p = .932$, they indicated a significant increase in the likelihood of traveling independently to such buildings if given access to an indoor navigation system providing real-time guidance information, as was evaluated in this study (question #4), $V = 54$, $Z = 2.40$, $r = 0.76$, $p = .024$.

7 GENERAL DISCUSSION

The primary motivation of this article was to evaluate *in situ* indoor route navigation performance by a broad age range of BVI navigators, manipulating when the accessible route guidance information was presented (e.g., before navigation or during navigation). We conclude this article by discussing the findings with respect to our motivating research questions of interest.

7.1 RQ1: Does Navigation Performance Differ as a Function of Perceptually Based vs. Memory-based Information Access?

The most important behavioral outcomes of this study are the results from the route completion and bystander request measures. These data provide compelling evidence that use of the system by BVI participants in a real-time (aided) mode led to more accurate (ability to correctly complete the route) and more confident (fewer requests for assistance) overall route navigation performance than was observed by the same group in memory-based (unaided) conditions. These findings demonstrate that increasing access to context-sensitive nonvisual route information reduces cognitive load on working memory while navigating; results that clearly support the efficacy of using real-time navigation systems.

The expected advantage for greater accuracy (less errors) when using the system during route navigation compared to memory was not statistically significant, although the numeric results showing almost 50% more errors when not using the system (23 vs. 16 errors, respectively) were in the predicted direction (see Figure 3). The higher-than-predicted errors when using the system suggest that the need for users to match environmental perception with the narrative descriptions in the system-aided condition may have introduced "noise" in the process that perhaps would not have manifested if using a fully automated system based on real-time localization technologies. To address this question, future work is needed to directly compare these two techniques for conveying real-time information during navigation.

In contrast to the route completion and bystander assistance variables, the route navigation time measure was quite noisy and not very informative. This outcome was likely a result of participants being encouraged to stop walking when listening to the route instructions or beacon information in the system-aided conditions. Although done as a safety precaution, this guidance led to many stops along the route, which artificially increased the total time compared to the unaided BVI condition or the corresponding aided sighted condition.

7.2 RQ2: Does BVI Navigation Performance Differ as a Function of Participant Age?

Perhaps the most surprising and impactful outcome of this study are the results observed between younger and older BVI adults. Our results showing highly similar performance between participant age groups across all of the dependent measures demonstrates that not only did older adults benefit from use of the system, but they were also as accurate and confident with its operation as their younger peers. These findings suggest: (1) that healthy older adults who are blind are as likely to benefit from the development of new information-access technology supporting navigation as younger BVI travelers and (2) that far more research is needed with this demographic to tease apart performance metrics evaluating whether age has differential impacts on use of navigation systems. While the current data revealed no such evidence, the samples were small, and all tasks relied on egocentric behaviors. The literature suggests that when age-related differences occur, at least with sighted adults over 60, they tend to disproportionately impact allocentric vs. egocentric tasks, such as map reproduction and pointing between two landmarks independent of the user's current heading and position [62, 63, 67]. While it is possible that performance differences may have manifested between age groups on different tasks, the current findings demonstrating nearly identical performance as a function of age are of note given that the vast majority of vision loss occurs in people over 65 years of age [26, 27]. To better understand the behavior of this older demographic in realistic navigation scenarios, greater focus should be given to conducting performance-based behavioral research emphasizing ecological validity (i.e., testing in the "wild") and use of more representative sampling including an older participant cohort. The prevailing practice of evaluating technology with only younger participants, as evidenced by the extant literature reviewed in the introduction on BVI navigation systems, is partly explained by younger people generally being more tech savvy than older adults and partially due to balancing research interests with practical challenges related to recruitment of populations of difference [79]. However, as many spatial abilities are known to decline with age, and the incidence of visual impairment is disproportionately represented in older adults, it is critical that this rapidly growing demographic be included in more studies evaluating spatial technologies or those assessing how technology may improve spatial performance (as was our focus here).

7.3 RQ3: Does Navigation Performance Using the Real-time System Differ as a Function of Visual Status?

The remarkable similarities in bystander requests and route completion accuracy between BVI participants and sighted controls in the system-aided condition make two important contributions to the literature. First, they provide empirical verification that the verbal information delivered to BVI users by the system is sufficient to support accurate performance as compared to the same information plus vision (i.e., as with the sighted controls). It could be argued that the sighted participants may have been disadvantaged by use of the system, as the attributes described by the verbal messages may not have mapped onto what they would "normally" have focused on during visually guided navigation. However, we think this unlikely, as they received the exact same route instructions and task, employed the same interface interactions, and importantly, could readily match the verbal information with its visual analogs in the environment, as all cues were salient across modality. Indeed, given that sighted participants obviously had access to far more information about their surroundings during navigation than the BVI participants, the finding of functionally equivalent performance between groups is even more remarkable and speaks to the value of information provided by the system. This outcome supports our information access argument that the type of information provided to support the task is more important than the overall amount of available information.

Second, the results of this comparison speak to basic theories about spatial information processing between people with and without vision, especially those arguing that BVI performance cannot be on par with their sighted peers, as visual experience is a prerequisite for accurate spatial interactions. (For an excellent review of this literature, see Reference [80].) The current results demonstrate that when sufficient nonvisual navigational information is available, the performance differences frequently cited as manifesting between BVI and sighted navigators (as reviewed in References [45, 59]) can be completely eliminated. The observed performance similarity between sighted and BVI groups when using the system provides new empirical support for the modern conception that most spatial deficits ascribed to blind navigation are due to insufficient access to key environmental information, rather than to the role of visual experience or as a necessary consequence of vision loss (see Reference [55] for a detailed discussion). Further support for this perspective comes from the comparison of BVI performance with and without the system. Where both conditions provided access to the same information, having perceptual access to context-relevant information in the system-aided condition eliminated the manifest deficits observed in the memory-based condition, as would be predicted from the information-access interpretation of blind navigation.

7.4 RQ4: Can the User Effectively Collaborate with the System to Support Route Navigation?

The high level of route completion accuracy observed with the system in this study suggests the answer is yes. However, the number of navigation errors found when using the system also suggests that the need for users to match their environmental perception with the narrative descriptions in the system-aided condition may have introduced "noise" in the process. While we continue to believe in the principle of the user as a sensor for supporting user engagement and global spatial learning, there may be a trade-off of utility and accuracy. That is, while this process may indeed improve user attention to individual route steps and an understanding of their overall environmental relation, it may occur at the cost of decreased temporal efficiency and increased localization errors. Future work is clearly needed to directly investigate the benefits of "the user as a sensor" vs. having automated instructions in terms of attentional demands and behavioral performance on

Table 7. User-indicated Preferences for Device Placement from Question 5 (see Appendix B)

Preference for device placement (n = 14)	
Hand-held	29%
Hands-free	64%
Either Hand-held or Hands-free	7%

a range of tasks including route guidance, spatial updating, spatial inference, and cognitive map development.

Navigation times in system-aided conditions were also longer than expected. One explanation for this relates to the requirement of the user to frequently interact with the interface as part of the "user as a sensor" model. Many users struggled initially in managing the touch-screen interaction while simultaneously using their cane or guide dog, as they generally used both hands to interact with the system, one to hold the phone and the other to perform the flick gestures for interacting with the route instructions. Indeed, use of this application by BVI people who also use mobility aids would leave them with no free hands for other tasks, thus making opening doors, pushing elevator buttons, or holding their morning coffee challenging. These observed interaction challenges, and their resultant effect on the behavioral outcomes, provide important insight about improvements of this system (and other related projects) requiring the user to constantly interact with the system. With respect to this issue, most participants indicated a preference for hands-free interaction (see Table 7).

Additionally, 57% of participants indicated that they would prefer to use this device with a headset, instead of the system speaker as we used here, as this could reduce ambient environmental factors interfering with hearing/interpreting the narrative information. To reduce masking of important auditory environmental information (e.g., traffic flow), we suggest that future incarnations of speech-based information-access devices used during independent travel should employ bone-conducting headphones, as they can convey either mono or stereo information without blocking the ears.

In most of the studies on accessible navigation systems (as described in Section 2), the verbal descriptions automatically trigger/advance as the user travels a route. In the current work, users were required to manually advance route steps, similar to procedures used in References [15, 74]. The advantage of this approach is that participants could easily repeat the message for the current step or quickly flick back-and-forth between instructional steps to obtain look-ahead information about the route or to review where they were previously. As was discussed in the introduction, we believe that this ability to move between steps and get an idea of the route/environmental parameters with respect to the current step is important for learning global structure and for maintaining situational awareness and active attention. However, we also recognize that having the ability to automate the progression of the messages at each instructional step, or to use voice commands to interact with the system to move between steps, may be more natural when traveling. A design modification involving easier step-by-step transitions is supported by our open-ended survey data (question 6 of Appendix B), where 13 of 14 participants indicated a preference for multimodal input incorporating voice and touchscreen interactions. Not only would this interaction style make it faster and easier to interact with the system, it would also free up one or both hands, while still allowing functionality to test the user as a sensor.

7.5 User Feedback and Design Considerations

In addition to evaluating behavioral performance with the system, another aspect of this study was to solicit user feedback on the content and structure of real-time narrative information

Table 8. User-indicated Preferences from Questions 7, 8, & 9 (See Appendix B)

User-indicated Preferences	
Would review route info ahead of time (if possible)	84% ($n = 13$)
Access to info about global route configuration at start	64% ($n = 14$)
Would prefer multimodal output	79% ($n = 14$)

supporting navigation without vision. Optimizing instructions to be clear and intuitive, while maximizing spatial precision and minimizing spatial uncertainty, is important for the development of narrative-based navigation systems. Could improvement of our instructions based on the empirical findings and user feedback further reduce the incidence of errors and bystander requests? We believe the answer is yes and the current data (both quantitative and qualitative) point at some of the modifications that might be most beneficial.

Evaluation of the error data revealed that some of the mistakes made in the system-aided conditions may be due to the phrasing used in the instructional steps (see Appendix A). For instance, the elevator lobby entry was the source of the most errors among both sighted and blind participants (accounting for 30% of the sighted participant error and 8% of the BVI participant error). This suggests that some errors were due to insufficient description clarity offered by the application at a confusing environmental location. The description of this lobby was a long instructional step, with multiple pieces of information that provided an overview of the space along with the actions to take. It may be better to nest such instructions where a simple action-based instruction is provided, with a choice to receive an additional global overview description if desired. Using a nested/layered description logic and a dialog-based interface to interact with the system in a natural, hands-free manner is something that should be considered in future system development. Future narrative information should either rely on more salient landmarks as references or if the location of a potentially ambiguous landmark is critical, should explicitly emphasize that use of a secondary cue (e.g., listening for a change in reflected sound or feeling with the hand) may be helpful in detection [26].

Post-survey responses also elucidated that some aspects of the narrative descriptions were confusing or disliked. For instance, 28.5% of the BVI users reported that they did not like or were confused by the use of distance measures in the instructions (Appendix B, Question #3). With our description protocol, all distance information was followed by a landmark, serving as the "destination" or completion point of that instructional step. However, many users over-emphasized the distance measures (or did not understand the information) and thus did not use the landmark as a cue to confirm their position, as we intended. In future implementations, it may be beneficial to reverse the order of operations in our description logic, e.g., landmark information is followed by metric information, allowing users to focus their attention on the landmarks and to use distance cues as a supplementary reference to determine approximate landmark location. For instance, Route 1 (Step 3) could be rephrased from "Walk 60 feet to a set of closed fire doors" to "Walk to a set of closed fire doors in 60 feet," which would follow the alternate Verb ⇨ landmark/destination ⇨ Distance description logic.

Responses to question 7 suggested a strong preference (Table 8) for multimodal output from the system. This could include synthesized speech to provide narrative information (as we did here) along with haptic/vibration cues from the device to convey spatial information about the route or map (see Reference [81] for such an incarnation), or even high-contrast visual maps for use by people with residual vision (as are available from the ClickAndGo wayfinding service). Finally, question 4, regarding system improvements, suggested a need for using a different beacon voice from other narrative information and separate instructions for dog and cane users. This latter point should be further investigated, as our informal observations during the study suggested that the information used, exploratory strategies, and attentional resources widely differed between users of these two mobility aids.

8 CONCLUSION

In conclusion, the outcomes of this study demonstrate the efficacy of using real-time spatial information for improving the accuracy and confidence of route navigation by a broad age range of BVI travelers in unfamiliar indoor environments. The most important results provide much-needed guidance for specifying the information requirements and refining the interface design for future development of accessible real-time, smartphone-based navigation systems. The current results also demonstrate that older adults who may be losing their vision and are experiencing difficulties in navigating would significantly benefit from access to such a system. Finally, these results have broader impact to anybody who is using narrative instructions to guide navigation in low-luminance environments, e.g., firefighters in smoky environments, emergency management personnel in buildings without electricity, or for eyes-free situations where visual attention is needed elsewhere.

APPENDIX A

Step-by-step route descriptions for each of the four routes as provided to the participants using the smartphone either in advance of travel (unaided and pre-journey unaided conditions) or in real-time during navigation (aided and pre-journey aided conditions).

Route 1: Disability Services to Media Services (225 ft, 68.6 m).

1. Enter the doors. Walk 20 feet to a wall and turn left. Walk ahead 20 feet to a wall with an intersecting hallway to the right.
2. Turn right. Walk 60 feet to a set of closed fire doors.
3. Enter and walk 25 feet to a wall. Turn right and enter the door to the stairwell landing.
4. Be aware there are descending stairs straight ahead. Turn left and follow the left wall to another pull door.
5. Enter the door into the north hallway of Horace Mann Hall. Walk 60 feet to a wall with an intersecting hallway to the left.
6. Turn left. Walk 15 feet to the second door on the left, Media Services.
7. You have reached your destination.

Route 2: Thorndike Security Booth to Cowin Room 150 (375 ft, 114.3 m).

1. Position yourself with 120th street behind you, and the Thorndike security booth on your right side. You are facing a narrow driveway leading towards Thompson and Thorndike Hall.
2. Walk 60 feet following the left side wall to the 1st door on the left, which is the Thompson side door.
3. Enter and walk 25 feet to a wall with an intersecting hallway to the left.
4. Turn left. Walk 10 feet to a set of automatic doors.
5. Enter and turn right into the main Thompson hallway.
6. Walk 30 feet to a large central statue and intersecting hallway.
7. Continue ahead 60 feet to a set of closed hallway doors.
8. Enter the doors into Horace Mann Hall and walk ahead 60 feet to a classroom door with an intersecting hallway to the right.

9. Turn right and walk 125 feet to a set of stairwell doors. At the halfway point you will pass the Cowin foyer.
10. To the left of the stairwell doors is the door to Cowin Room 150. Turn left and enter.
11. You have reached your destination.

Route 3: Zankel Security Entrance to Zankel Help Desk (100 ft, 30.5 m).

1. Facing the Zankel security desk, turn right and walk 10 feet to ascending stairs.
2. Locate a left side handrail and ascend stairs to a stone floor hallway.
3. Walk 15 feet across the hallway to opposite hallway wall.
4. Turn right and trail the wall a few feet until you find a pull door.
5. Enter into elevator lobby. The elevator is located at 11 o'clock, 10 feet away. Be aware of descending stairs at 10 o'clock and 15 feet away, and ascending stairs directly ahead, 8 feet away.
6. To avoid the descending stairs, follow the right-side wall past the ascending stairs until you reach the elevator. It is no more than 12 feet.
7. Enter the elevator, and exit on floor G into elevator lobby. Walk to the door located at 11 o'clock, 10 feet away.
8. Pass through the doors, and turn left into a slightly textured hallway.
9. Walk 20 feet where a downslope begins. Continue 20 feet to the end of the downslope and a left side intersecting hallway.
10. Turn left. Walk ahead a few feet to the first door on the left. This is Room 23-A, Zankel Help Desk.
11. You have reached your destination.

Route 4: Zankel Security Entrance to Zankel Room 218 (185 ft, 56.4 m).

1. Facing the Zankel security desk, turn right and walk 10 feet to ascending stairs.
2. Locate a left side handrail and ascend stairs to a stone floor hallway.
3. Walk 15 feet across the hallway to opposite hallway wall.
4. Turn right and trail the wall a few feet until you find a pull door.
5. Enter into elevator lobby. The elevator is located at 11 o'clock, 10 feet away. Be aware of descending stairs at 10 o'clock and 15 feet away, and ascending stairs directly ahead, 8 feet away.
6. To avoid the descending steps, follow the right-side wall past the ascending stairs until you reach the elevator. It is no more than 12 feet.
7. Enter the elevator, and exit on floor 2 into elevator lobby. Walk to the door located at 1 o'clock, 10 feet away.
8. Pass through doors into a wooden floored hallway.
9. Turn right and walk 60 feet to a water fountain. Continue ahead 65 feet to an intersecting hallway on the right.
10. Turn right. Walk 8 feet to the first door on the left, Room 218.
11. You have reached your destination.

APPENDIX B

Open-*ended* survey questions.

1. What part of the navigation route was most challenging?
2. Please list what you liked about the current system.
3. Please list what you didn't like about the current system

4. What suggestions do you have for our user interface so as to better provide information?
5. What is your preference for placement of the device? For example, hand-held, placed in a pocket, clipped to a belt, other?
6. How would you want to provide information to the system? (For instance, what input channels should be used?)
7. How would you want to receive information from the system? (For instance, what output channels should be used?)
8. Is it helpful to know the global configuration of the route at the beginning? For example, this is an L-shaped route.
9. Would you use a system that offered access to a route before going to the building? Do you think this would help once navigating in the physical space?

ACKNOWLEDGMENT

We thank Richard Keller for his assistance in procuring the test space at Teachers College.

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Received January 2019; revised April 2020; accepted June 2020