Supporting Spatial Awareness and Independent Wayfinding for Pedestrians with Visual Impairments

Rayoung Yang, Sangmi Park, Sonali R. Mishra, Zhenan Hong,
Clint Newsom, Hyeon Joo, Erik Hofer, Mark W. Newman
School of Information, University of Michigan
Ann Arbor, MI 48109, USA
{rayang, sangmipa, srmishra, guoerhzn, newsomc, thejoo, ehofer, mwnewman} @ umich.edu

ABSTRACT
Much of the information designed to help people navigate the built environment is conveyed through visual channels, which means it is not accessible to people with visual impairments. Due to this limitation, travelers with visual impairments often have difficulty navigating and discovering locations in unfamiliar environments, which reduces their sense of independence with respect to traveling by foot. In this paper, we examine how mobile location-based computing systems can be used to increase the feeling of independence in travelers with visual impairments. A set of formative interviews with people with visual impairments showed that increasing one's general spatial awareness is the key to greater independence. This insight guided the design of Talking Points 3 (TP3), a mobile location-aware system for people with visual impairments that seeks to increase the legibility of the environment for its users in order to facilitate navigating to desired locations, exploration, serendipitous discovery, and improvisation. We conducted studies with eight legally blind participants in three campus buildings in order to explore how and to what extent TP3 helps promote spatial awareness for its users. The results shed light on how TP3 helped users find destinations in unfamiliar environments, but also allowed them to discover new points of interest, improvise solutions to problems encountered, develop personalized strategies for navigating, and, in general, enjoy a greater sense of independence.

Categories and Subject Descriptors
H.5.2 [**Information Interfaces and Presentation**]: User Interfaces – *User-centered design*; K.4.2 [**Computers and Society**]: Social Issues – Assistive technologies for persons with disabilities

General Terms
Design, Human Factors

Keywords
Accessibility, Spatial Awareness, Wayfinding, Mobile Computing

1. INTRODUCTION
Pedestrians with visual impairments miss out on a great deal of information about their immediate environment that sighted individuals may take for granted. While many are adept at compensating for missed information through increased awareness of other environmental cues [14] and the use of navigational aids, both low-tech (e.g., white canes or guide dogs) and high-tech (e.g., GPS devices or electronic obstacle avoidance systems), there are still many situations in which individuals with visual impairments are not able to travel as independently as they would like. For individuals with visual impairments, traveling to a new environment can be a particularly challenging experience. As a result, when travelers with visual impairments seek out unfamiliar destinations, they often need to plan ahead extensively in order to obtain and memorize directions, and many seek assistance from others—including friends, family members, and professional mobility trainers—in order to familiarize themselves with an unknown place. Even when traveling somewhat familiar routes, it can be challenging to handle unforeseen needs that arise during a journey, such as finding food, drink, or a toilet. In essence, each new need can require the mastery of an additional route, and it can be difficult to anticipate all the routes one might need to know in advance. Additionally, travelers may miss the chance to serendipitously discover new information about their environments, such as new points of interest, and special events.

Based on the insights derived from formative interviews [19], we designed a system that would provide greater independence for travelers with visual impairments by increasing their awareness of aspects of their immediate environment. In particular, we sought to leverage the potential of location-based mobile computing technology in order to add a layer of "legibility" to the environment that would help foster greater spatial awareness, which would in turn help with wayfinding activities, including both task-oriented and exploratory traveling. By focusing on spatial awareness rather than efficiently directing users to their destinations, our approach differs from the bulk of prior work in this area. Our view is that placing the user in control of the information accessed and encouraging them to explore information about locations not directly linked to a particular navigational goal will help foster a greater sense of spatial awareness while also allowing users to find specific destinations. These specific goals are in the service of the larger goal of increasing individuals' sense of independence and confidence in exploring new destinations, regardless of their level of sight.

The result of our design is Talking Points 3 (TP3). As the name suggests, TP3 is the third in a series of systems that have been developed to leverage positioning technology to assist people with visual impairments. Talking Points 1 [5] used a mobile RFID reader to detect tags in the environment, which would result in descriptions of the tagged objects or locations being communicated to the participant. Since travelers with visual impairments cannot be assumed to know where the tags are placed, the RFID reader required a great deal of power to be able

ASSETS'11, October 24-26, 2011, Dundee, Scotland, UK.

to detect tags at a sufficient distance. The power demands were deemed too great for a truly mobile system, and so Talking Points 2 [21] was designed to use commodity Bluetooth hardware for detecting Bluetooth beacons in the environment. This second generation of the system also included support for richer data about points of interest and a shared database supporting community generated content contributions, but lacked a workable strategy for deciding which points of interest would be the most valuable to include and what information would be most useful to our target users. TP3, then, was redesigned from the ground up, starting with formative interviews, followed by design, prototype development, and a user study. As described in this paper, TP3's design includes a comprehensive framework for deciding which points of interest to present to users, an indoor/outdoor coordinate-based positioning system that provides users with a greater range of options for exploring their environment, and a combination of push- and pull-based information retrieval that allows users to exert more or less initiative in the interaction with the system, depending on the task and personal preference. TP3 is implemented as a smartphone application that uses GPS, WiFi, and a compass to determine the user's location and orientation and communicates with a web-based database to retrieve information about nearby locations.

In this paper, we describe the design of the TP3 system and the results of a user study with eight legally blind participants who used TP3 to navigate through three large buildings on a university campus. Through this, we aim to make two main contributions:

1. An approach to supporting generalized spatial awareness consisting of
   a. making the environment legible for travelers with visual impairments by representing *paths*, *areas*, *landmarks*, *decision points*, *functional elements*, and *physical characteristics of the environment*, and
   b. supporting user control by providing a set of mechanisms for interactively browsing spatial information rather than providing turn-by-turn directions.
2. An evaluation of our approach, demonstrating that the above features
   a. help users navigate unfamiliar environments that they would otherwise find intimidating, and
   b. support important aspects of spatial awareness beyond procedural wayfinding, potentially giving travelers with visual impairments a greater sense of independence.

2. RELATED WORK

The idea of providing location-based orientation and navigation assistance to pedestrians with visual impairments is not new. The seminal work of Loomis, et al. [11] described the essential components of such a system as comprising a positioning system, a geographical information system (GIS), and a user interface. Subsequent work has focused on providing solutions in one or more aspects of this basic framework. For example, while most systems in this class have used GPS-based positioning, other solutions have been proposed to support indoor navigation (e.g., [7]) and fine-grained object finding (e.g., [12]). Regarding the GIS component, systems have been proposed that provide more detailed location data (e.g., [7]) more sophisticated route calculations (e.g., [18]), and the ability of end-users to update the GIS database directly (e.g., [24]). Perhaps the largest number of projects have focused on exploring alternatives for the user interface, proposing approaches ranging from verbal instructions (e.g., [16]), to non-verbal auditory cues (e.g., [24]), to tactile feedback (e.g., [17]). In addition to the research systems sampled above, commercial/open-source systems based on GPS and widely available GIS data have been marketed for a number of years. Notable examples in this category include the Trekker Breeze[1], which includes GPS positioning, a button-based input device, and voice-based output for spatialized information and route instructions; and the feely available Loadstone GPS[2] which allows users to create and update information about points of interest with each other through a shared database.

While these systems cover a wide range, there are a few generalizations that can be made. First, with a few exceptions (e.g., [20] and Loadstone GPS), the emphasis of much of the work in this area has been on providing route-based instructions to specific, pre-selected locations. While this is surely an important goal, it fails to address other important goals, such as exploration, serendipitous location discovery, and general spatial awareness. Indeed, several authors have suggested that systems that focus on providing turn-by-turn navigation instructions can cause users to disengage from their surroundings [9] and may impact their ability to master the spatial organization of the environment [8]. Second, due in part to the emphasis on providing route instructions, little work has been done to describe the structure of the *content* that should be represented in a system to support general spatial awareness, rather than primarily procedural route finding. A notable exception is [6], which determined a broad set of preferences governing what individuals with visual impairments would want from a navigation system, though this study did not distinguish between needs related to navigational efficiency and general spatial awareness.

3. THE TALKING POINTS SYSTEM

Talking Points 3 is a location- and orientation-aware smartphone-based system that provides information to users about nearby points of interest in the environment. It supports a set of interactive mechanisms for accessing information about the local environment, with all information being conveyed to the user via text-to-speech through the smartphone's audio output. Information is stored in a central database that can be accessed freely and updated by users, community members, and stakeholders associated with the locations represented in the database. The key distinguishing features of TP3 are the structure provided for determining which location data to include and the interactive controls for accessing that data.

The design of TP3 is based on a formative study that explored how people with visual impairments orient themselves and navigate when traveling [19]. That study highlighted that while navigating familiar routes is generally not problematic for travelers, unfamiliar routes can pose a daunting challenge. Familiar routes can pose problems as well, especially when changes to the routes occur due to the appearance of physical barriers (e.g., construction or temporary blockages) or changes to environmental cues (e.g., a change in restaurant ownership causing a change in the ambient scent). Moreover, the study found that existing GPS-based navigation solutions can be unsatisfactory for certain needs such as error recovery, exploration, or dealing with route alteration due to unexpected needs. These systems provide information primarily in the form of turn-by-turn instructions, which were seen as particularly fragile in the face of

[1] http://www.humanware.com/en-usa/products/blindness/talking_gps/trekker_breeze/_details/id_101/trekker_breeze_handheld_talking_gps.html

[2] http://www.loadstone-gps.com/

dynamic environments. Based on the findings, as well as the limitations of prior work noted above, we decided to focus the design of TP3 around increasing the "legibility" of the environment rather than simply helping people find specific destinations.

Lynch [13] describes the *legibility* of an environment as the ease with which people can draw a mental image of the environment and use it to orient themselves and navigate to its different parts. Passini offers a more specialized definition of legibility as the clues embedded in a built environment that enable users to navigate through it [15]. Arthur and Passini [1] describe legibility as crucial to wayfinding, characterizing wayfinding as a constant decision-making process in which decisions are usually made at key areas, called decision points. By focusing on enhancing legibility, we seek to go beyond simply directing pedestrians with visual impairments to specific locations. With a focus on enhancing legibility in order to foster greater spatial awareness, we designed TP3 to meet three high level goals:

1. TP3 should support generalized environmental legibility by providing spatially-anchored information along with interactive controls for allowing users to explore the space dynamically and according to their own navigational and/or exploratory preferences.
2. TP3 should provide information about spatial features and points of interest specifically relevant to the needs of travelers with visual impairments in addition to information of interest to a wider audience.
3. To accommodate the increased information demands suggested by (2), TP3 should allow community-generated content to be attached to spatial anchors, allowing the most relevant content to be generated by the community members who value it most.

3.1 Content Structure

The basic unit of information in TP3, as in many location-based information systems, is the Point of Interest (POI). At base, a POI is a record that maps information to a specific geographical point and consists, at a minimum, of the point's latitude, longitude, altitude, name, and type. The POI data structure is extensible, allowing specific POI types to include additional information such as hours of operation, detailed description, and user comments.

In a study comparing blind and sighted pedestrian navigation, Passini and Proulx [1] reported that "[t]he blind participants made significantly more wayfinding decisions and used more units of information (e.g., landmarks) than did the sighted group," highlighting the fact that travelers with visual impairments would require detailed information about the environment that differs in key ways from the information that would be desired by sighted users. In order to support the acquisition of sufficiently detailed information, we follow [24] in supporting community-generated content. Moreover, we suggest that information for each site (e.g., building, campus, neighborhood) be "seeded" manually by working with the site's stakeholders to identify key POIs of each type and collect crucial information like physical description, layout, and type-specific information. The seeded information should ideally be enough to provide basic utility to the travelers, subsequently allowing the information to be supplemented by community members [22].

3.1.1 POI Types

Lynch [13] identifies key elements of space that aid in orientation and navigation through cities: landmarks, nodes, paths, edges and districts. Arthur and Passini state that making informed decisions at decision points is crucial for successful wayfinding [1]. Our interviewees [19] identified additional specific location types that pedestrians with visual impairments find useful in navigation, including entrances, doorways, staircases, and restrooms. These findings, along with Lynch's more general framework, suggest that an effective wayfinding solution for people with visual impairments must take into consideration a variety of different types of spatial information. We base contextual information provided by TP3 on the following types of locations and features, here adapted to the indoor environment:

- Paths are channels through which people travel, such as corridors, pathways, hallways (derived from Lynch's *paths*)
- Areas are spaces with recognizable characteristics, such as food courts, lobbies, atriums (derived from Lynch's *districts*)
- Landmarks are particular places which can be used as a reference point, such as stores, restaurants, classrooms (derived from Lynch's *landmarks*)
- Decision Points are focal point—the intersections of Paths (derived from Arthur and Passini's *decision points*)
- Functional elements are locations that support navigation and other needs, such as restrooms, stairs, entrances, elevators (derived from our formative study)

3.1.2 POI Metadata

Völkel et al. [23] note that people with visual impairments require geographic annotations as well as specific kinds of POIs to support orientation and navigation. Specifically, information regarding obstacles, layout of streets and paths, and environmental cues such as ground surface are necessary to complement missing information on existing map data. To address this need, each POI in TP3 has a mandatory "physical characteristics" field to go along with the aforementioned latitude, longitude, altitude, name, type, and arbitrary type-specific annotation fields. The physical characteristics field is meant to capture descriptive information about each POI, such as the physical layout, salient characteristics like railings or columns, and a description of the entryway.

3.2 Interacting with the Content

An additional challenge in providing contextual information is to determine how the system will provide that information to the user. Cheverst et al. [2], note that both "pushed" and "pulled" information have a role to play in location-based systems, where information which is immediately relevant should be "pushed" to users, whereas the system should allow users to "pull" more detailed information at their discretion. We designed TP3 to push selected information about the immediate surroundings to the user, while making available more detailed information about immediate and distant surroundings for the user to retrieve at will.

3.2.1 POI Retrieval Mechanisms

As illustrated in Figure 1, TP3 supports three mechanisms to allow users to access information about points of interest:

- Automatic Notification: TP3 automatically notifies users of POIs within 10 feet of their current position. The notification consists of a sound alert, the name of the POI, and the user's distance to the POI in feet.

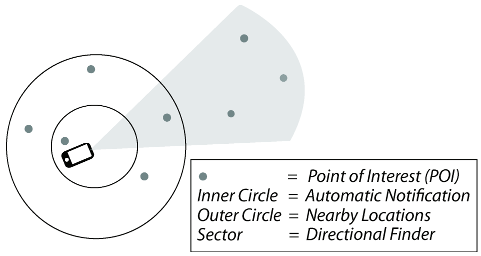

Figure 1. Talking Points 3 provides three mechanisms to allow users to access information about points of interest.

- Nearby Locations: Users can request a list of locations within 30 feet of their current position. When scrolling down the list, a user is given the name of the POI and the distance to it.
- Directional Finder: Users can point the phone and click a button to pull a list of POIs up to 100 feet away within a 45 degree angle of that direction. For example, if a user points the phone northwest, TP3 might say, "You are facing northwest, there are three locations in this direction." Direction is determined using an Android compass function.

3.2.2 *User Interface*

TP3 was designed with two main modes representing the Nearby Locations and Directional Finder features. By default, TP3's user interface provides the list of Nearby Locations, allowing users to access information about nearby POIs. To access information about more distant POIs, users can press a button to switch to the Directional Finder mode. Automatic Notifications are pushed to users in either mode.

Users interact with the TP3 client using a set of five simple touch screen gestures (up, down, left, right, and double-tap), a single button press, and a shake gesture. These seven input operations can be implemented in different ways for different hardware. Roughly speaking, the directional gestures are used for navigating through the TP3 menu hierarchy to retrieve detailed POI information, a double tap is used for selecting a menu item of interest, and button clicking and phone shaking are used for switching between the Nearby Locations and Directional Finder modes. All of these gestures were designed to be simple, learnable, and one-handed, so that they could be made by users who were also holding a cane or a guide dog.

3.3 Implementation

As shown in Figure 2, the current implementation of TP3 employs a client-server architecture with a Java-based Android client running on a Nexus One smartphone. The client communicates with a Ruby on Rails-based server via HTTP. The server maintains the database of POIs, and supplies the client with a continually refreshed set of nearby POIs based on the currently detected location and compass heading. The POI database is updatable via a web interface, which is also served by Ruby on Rails. On the client side, all information about points of interest are communicated to the user via text-to-speech, as are most system menu and feedback messages, though audio and haptic cues are also used to support low-level interaction such as the successful completion of a command.

TP3 depends on receiving continuous updates about the user's current position and orientation. The Nexus One features GPS-based positioning and a built-in compass, and our prototype makes use of both in outdoor environments. Additionally, we are in the process of implementing an indoor positioning system (IPS)

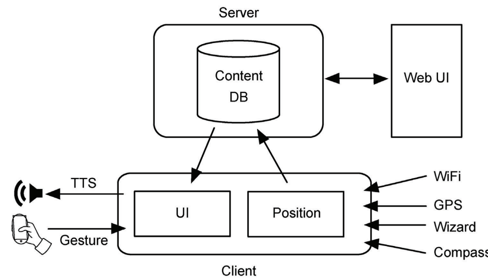

Figure 2. Talking Points System Architecture

for Android based on WiFi trilateration [3]. Our IPS performs well in the lab, achieving an average positioning error of less than 5 meters under controlled conditions (i.e., the mobile client receiving a strong signal from at least three access points, which are all less than 20 meters away). However, achieving such results is much more difficult in a naturalistic, uncontrolled setting, where WiFi access points may be spaced unevenly throughout the environment and, indeed, we found that there were large regions of the buildings we selected for our target deployment where determining an accurate position via trilateration was impossible because the client could not see at least three access points. We also learned that the Nexus One compass does not work well in some indoor environments due to magnetic interference, and we are investigating ways to overcome this limitation for indoor operation. Thus, to test the *user experience* of TP3 while working to improve the IPS and orientation system to an acceptable level, we developed a "Wizard of Oz" (WOz) positioning tool that allows us to simulate the detection of users' locations and orientations by clicking on a web-based building map. As we will describe in the next section, the wizard tool proved to be essential for our user testing efforts.

4. USER STUDY DESIGN

The goal of our study was to determine whether TP3 increased the legibility of the environment for its users in order to assist in their wayfinding. We wanted to explore whether and how TP3 enhances spatial awareness; whether it gives users a greater sense of independence in traveling; and what the strengths, weaknesses, and usability problems of the prototype were. Because indoor navigation is not yet well supported for pedestrians with visual impairments, we decided to test our system's strength in an indoor setting. We elected not to execute an experimental study design due to the difficulty of creating an appropriate control condition. Two control alternatives were considered: a no-assistance condition, in which the only aid given would consist of verbal instructions given in advance; and an orientation condition, in which participants would be given an orientation to the building by a sighted guide, resembling a standard orientation given by mobility trainers. However, a set of pilot studies showed us that the no-assistance condition rendered the tasks nearly impossible for participants to complete and the orientation condition was too easy because the typical interaction with an orientation specialist includes highly personalized instructions that would be infeasible to replicate in an automated system. Choosing instead to conduct an exploratory study of the user experience of interacting with TP3, we designed the study to simulate a pedestrian with a visual impairment visiting an unfamiliar location. In addition to seeing whether participants could find a set of target locations, we were interested in learning whether TP3 would allow users to learn about additional locations of interest (i.e., ones not associated with any of the tasks) and observing specific ways that TP3 helped or hindered participants' ability to navigate in the new environment.

4.1 The Talking Points 3 Testbed

We selected three campus buildings for our testbed deployment based on their proximity to each other and the variety of environments they contained. They were a student union, an academic building containing classrooms and offices, and a mixed-use building containing a library and a number of specialized spaces for technical and creative work.

To prepare our system for the study, we analyzed each of the testing locations to identify the paths, areas, landmarks, decision points, and functional elements they contained. For each POI, we used the web-based editor to create a database entry including the name of the POI, its location, its type, a description of its physical characteristics, and any relevant information like hours of operation. Across all three buildings, we ended up "seeding" 68 POIs, though only a subset of these were actually used for the study tasks. No community-generated content was used in our study testbed—all content was created by the study team.

As mentioned in the previous section, our indoor positioning and orientation systems were not performing adequately, driving us to employ a Wizard of Oz (WOz) testing approach [4]. While choosing a WOz approach does not allow us to claim that the system we tested is currently deployable, we are confident that rapid improvement in the quality and cost-effectiveness of indoor positioning systems in recent years (e.g., [10], as well as commercial systems such as Ekahau[3] and Cisco MSE[4]) indicates that robust and accurate indoor positioning systems will be more and more common in the years to come.

Our WOz positioning tool was slightly more accurate than is currently achievable with existing approaches to WiFi positioning. While average estimation errors of around 2 meters have been achieved by several WiFi-based techniques (e.g., [10]), we determined that the average estimation error of our WOz tool was slightly less than 1 meter[5]. In retrospect it would have been a good idea to "fuzz" the output of the WOz tool to increase the error to a more realistic level, though as we will report later, our test participants experienced the WOz positioning system as being quite a bit less accurate than our 1 meter average error would suggest. This is most likely due to a 2-5 second lag between the WOz tool and the TP3 client, which resulted in a magnification of the inaccuracy of the position reports when the user was moving.

4.2 Task Selection and Design

When preparing for a visit to an unfamiliar building, people with visual impairments typically get directions either from the information desk or other people working at the destination, or from passers-by they encounter when arriving. Based on this information, we designed scenarios in which participants were given "natural" instructions for reaching their destination. These instructions included directions for where to turn at certain intersections along the route and select details about the destination.

We assumed that TP3 would have different levels of usefulness in fostering spatial awareness in different types of indoor environments, so we designed our tasks to include three different styles of floor layout. Specifically, participants had to travel through "regular" environments, which were characterized by rectilinear floor plans consisting of straight passageways intersecting at more or less right angles; "complex" areas consisting of passageways that intersect at odd angles or include multiple floors; and "open space" areas which lack features that might otherwise aid navigation such as sidewalks or walls to follow. Given the set of environments available in the selected buildings, we designed tasks that would expose participants to various layouts, while unifying the tasks with a coherent scenario:

(1) Your friend dropped you off at the information desk of the building where you're attending a meeting today. You arrived a little early, and wonder if you can get a drink before you go to the meeting. You ask the person at the information desk where you can get a drink and receive directions to a small shop in the first building. (2) After you get your drink, you want to go to the meeting. You remember the room number, so you ask the clerk at the store for directions. You receive directions to the meeting, which turns out to be in an adjacent building connected by a corridor. (3) During the meeting, you learn about a new design lab in the next building over. There's a project to compose music with electronic sound, and you'd like to hear one of the works. You have time to visit there before your friend is picking you up. One of the people at the meeting was heading in that direction, so he guides you to the information desk of the third building. There you ask where the design lab is and receive directions.

4.2.1 Directions

We asked two different information desk workers (at different times) for directions to our task destinations, to make sure that the directions we gave participants mirrored directions they might be given in reality. We were told which direction to go at each intersection along the route and details that would help identify critical points along the way. The directions we provided in each task prescribed routes with 1-4 decision points. As an example, the directions for task 1 were as follows:

Walk down the hallway until you reach the connector to D---. Before you enter the connector, turn left and walk straight. At the end of the hallway, there's a U---, convenience store, on your left.

4.3 Participants

We had eight legally blind participants (4 female, 4 male), meaning they had visual acuity of less than 20/400. Two participants traveled with guide dogs, five were cane travelers, and one traveled with her vision, which was sufficient for avoiding obstacles. All participants were very familiar with computing technology in general and were regular users of screen readers on personal computers. Three participants had experience using handheld touch screen devices.

4.4 Procedure and Data Analysis

Participants were asked to answer a short questionnaire about their visual impairment, navigation skills, and familiarity with assistive and touch screen technology. They were given a tutorial on the TP3 prototype, followed by a training session to allow participants to become familiar with the application. Training was conducted in a different part of the first building from the testing

[3] http://www.ekahau.com/products/real-time-location-system/overview.html

[4] http://www.cisco.com/en/US/products/ps9742/index.html

[5] This was determined by having one team member secretly select 60 locations on the map and position himself at those locations to establish "ground truth" while the team member who acted as "wizard" during the test followed him and attempted to select each position using the WOz tool. The difference between the two measurements for each point was used to calculate the average error.

locations, and participants practiced using TP3 while walking through a hallway with several locations around them.

After the training session, participants were presented with the scenario and asked to perform the three tasks described above. We asked participants to try their best to complete the tasks. There was no time limit. To begin each task, the test moderator guided the participant to a specific starting point and provided the directions to the destination following a written script. Participants were allowed to have the directions repeated until they understood the route. At any time during the task, participants could ask for the name of the destination or for the scripted directions to be repeated.

During the test, participants were asked by the moderator to think out loud as they did the tasks and two additional study members observed silently, recorded video, and took notes. If participants had trouble figuring out where they were and which way to go, the moderator encouraged them to try the appropriate functions of TP3 to reorient themselves. If the participant got lost or had much difficulty trying to orient themselves, the moderator gave clues by reminding them of TP3's functions or repeating the task instructions.

After each task, a study member asked brief questions about whether the task was easy or difficult and clarification questions for some of the actions participants took during the tasks. After participants had completed the tasks, we conducted a semi-structured interview to learn about their experience with TP3.

All sessions were audio and video taped for later analysis. While observing, team members also made notes of task completions and failures, moderator-provided help, critical incidents, bugs, observations, and user comments. Three to four team members were present for every user study session. After the conclusion of the sessions, two team members reviewed the observation notes and video and audio recordings to understand how the features of TP3 were used during task execution and how it did or did not help participants to accomplish their goals. They also examined comments and navigation patterns that related to other aspects of participants' experience of using TP3, including evidence of serendipitous discovery, route improvisation, and error recovery.

5. FINDINGS

All three tasks were completed successfully by all participants except for two failures in task 2 and two failures in task 3. P08 accounted for half of these, as he had great difficulty using TP3 and was unable to complete tasks 2 and 3. P03 believed she had completed task 3, but had actually found a neighboring location. P02 abandoned task 2 after struggling with it for some time as she had a time constraint and she did not attempt task 3.

Most users were able to complete the assigned tasks, despite usability issues we discovered with the touchscreen-based interface. While some of our participants were fluent with touchscreens, others were uncomfortable with them and struggled with making the correct gestures. Our sessions were also occasionally hampered by technical limitations, including issues with the WOz positioning tool, prototype malfunctions, and dropped internet connections. Because of these interruptions, we did not find completion time to be a useful metric; however, our perception is that participants completed the tasks within a reasonable amount of time. In addition to assessing task completion, we were interested in how TP3 was used during the tests. For much of each session, the Automatic Notifications were sufficient for participants to stay on the correct route. However, for open or complex areas, where there were fewer in-built cues like walls to guide participants along their route, the Automatic Notification was not always adequate. In these cases, participants found the Directional Finder useful for reorienting themselves. Consequently, the Directional Finder was used nearly twice as much in tasks 2 and 3, which featured more open and complex environments, than for task 1, which took place in a more regular environment.

In the remainder of this section, we will describe our specific observations that illustrate the benefits and weaknesses of TP3 and to demonstrate how TP3 helped participants navigate the environment, gave them a greater sense of spatial awareness, and increased their sense of independence.

5.1 Wayfinding

Throughout most of the test sessions, TP3 helped users orient themselves and make accurate wayfinding decisions. Although TP3 is not a turn-by-turn direction system, participants still reported that the system was useful for helping them find their destination. In general, participants found Automatic Notifications useful for determining if they were going in the right direction, and the Directional Finder helpful for deciding which direction to go. At the same time, there were differences in how people incorporated TP3 into their wayfinding strategies, indicating that TP3 can support different styles of navigation.

5.1.1 Staying on track

Most participants made use of the distance information included in each location report to determine whether they were going in the right direction. Three participants compared this process with the children's game "Hot or Cold" in which players find a hidden object by means of clues like "you're getting warmer" or "you're getting colder." Participants made heavy use of distance reports to determine if they were getting closer to or further away from target POIs and to determine whether to maintain their current course or go back. Some participants used the distance reports to decide when to switch to another mode of navigation entirely. In particular, as these participants came closer to their targets, they engaged other travelling skills to determine if they had reached their destination, such as feeling the wall for a door or a Braille sign, listening for sounds, or relying on their guide dogs.

5.1.2 Finding the way back: Recovery from errors

TP3 also helped users recover from errors. Two participants became disoriented at the start of the second task, which required participants to retrace their steps to get to a classroom in another building. One participant made a wrong turn and started walking in the opposite direction. When she realized she wasn't getting notified of any of the POIs she had passed before, she realized that she had taken a wrong turn and quickly went back. A second participant began in the right direction, but believed he was going the wrong way and headed back the way he had come. When he heard the Automatic Notification for his previous location at a convenience store, he remembered that he was supposed to turn left at that POI, and ultimately succeeded in finding his way. By providing environmental cues, TP3 allowed this participant to recognize his instructions rather than recall them with ease.

5.1.3 Navigating complex environment

Not surprisingly, participants in general found regular environments easier to navigate than open or complex spaces. Indeed, Some participants found the regular layout featured in task 1 simple enough to navigate that they felt they would have been able to find their destination without the aid of TP3, working only on the directions provided at the beginning of the task. Even these participants, however, found open and complex spaces much more challenging. In these environments, the Directional Finder helped participants determine which direction to go in by telling them what POIs lay ahead of them. As P02 noted, "[TP3] can make that open space a little less daunting because you can actually know [where to go]." Another participant commented that the Directional Finder was especially useful for him because his guide dog tended to lead him straight through open spaces. Without TP3, he might have missed a crucial turn and had more difficulty reaching his destination.

5.1.4 Developing individual strategies

Two interesting but distinct strategies emerged among participants for using TP3 to move them towards their destinations. The few participants who were comfortable navigating using cardinal directions would use the Directional Finder to try to find the direction of the next destination and then repeatedly check their heading (also using the Directional Finder) to determine if they were still on course. Other participants used the Directional Finder far less frequently, and would strike out in the direction in which they believed the next destination lay, waiting for an Automatic Notification to tell them when they had reached it. As some of these participants felt they were getting closer to the destination, they started using Nearby Locations to actively check if the destination was near, only occasionally using the Directional Finder to make sure they were still on track.

5.2 Spatial Awareness

5.2.1 Serendipitous discovery

TP3 allowed participants to gain serendipitous information about their surroundings to which people with visual impairments are not usually privy. While users may still follow directions from starting point to destination, they can use TP3 to learn about what they pass along the way. P01 exclaimed that TP3 "[made him] realize how much [he] really was missing before," commenting that, "It's always good to know what's around you. It expands the things that you can do." This information, including notices of new services and upcoming events, open hours, and the location of unsought objects like computer stations or bathrooms, can be of use in meeting future or unforeseen needs. Obtaining location information while en route, even when it is not specifically related to any predefined destination, may help users make informed decisions and spontaneously improvise new routes to various locations when necessary. On hearing a notification for the 'Piano Lounge,' P02 cited this serendipity as her favorite aspect of TP3: "Even if you didn't want to go to those particular places, it's kind of fun to know..., I could go and practice my piano." Additionally, several participants specifically noted that just knowing where the restrooms were was extremely valuable.

5.2.2 Supporting exploration

Although our study design did not explicitly encourage exploration *all* participants observed that TP3 would be useful for exploring new areas and discovering new locations around them. P07 pointed out that people with visual impairments often have difficulty exploring unfamiliar areas because they do not know what type of locations to expect. Moreover, they often find it unhelpful to ask sighted people for help in exploration: sighted consultants usually ask travelers where they want to go instead of explaining generally what lies in a certain direction. Nor are their directions always useful. P07 said, "I could go exploring, [I] could go into a non-familiar area and know what was there without the vagueness that you get from asking sighted people."

5.2.3 Description and physical characteristics

Participants found it useful hearing about the characteristics of specific POIs. For example, P01 was impressed that TP3 told him about a railing that guided the line at a Panda Express. P03 and P06 thought it was useful to know about the menu, hours, and products offered at various locations. They noted that user comments would be useful as well, once available. The physical descriptions which TP3 provided could also be useful in avoiding dangerous obstacles. P05 commented that it was great to hear that the store had an L-shaped counter, noting that, "If you didn't know that [it was an L-shaped counter] and you're at the register, you could potentially hurt yourself."

5.3 Independence

As noted in our formative study [19], when people with visual impairments learn about a new environment, they often need sighted people to assist them by describing main landmarks within the environment and helping them memorize routes by walking with them more than once. Thus travelers with visual impairments typically bring a sighted friend or guide with them when visiting a new building. However, this arrangement is not always convenient and can impose a significant time burden on both the traveler and their companion(s). This burden can constrain the extent to which travelers can explore new environments—travelers with visual impairments may be unwilling to travel or explore as much as they would like in order to minimize the demands upon their companion(s).

Six out of eight participants stated their belief that TP3 would increase their level of traveling skill, while one was neutral and one felt it would have a negative impact. Five out of eight participants stated that they believed they would feel a greater sense of independence with a system like TP3. Participants' specific statements highlight the reasons that TP3 fosters a greater sense of independence. One reason for increased confidence was that participants felt less anxious about getting lost. P05 described, "[With TP3] I honestly would feel like I can get where I need to be and if I get lost, I can find my way out." In addition to having increased confidence in finding specific destinations, participants felt that TP3 gave them more control by giving them more knowledge about the space around them. P01 commented that "Sighted guide[s]… couldn't possibly tell you all the stuff... [with] Talking Points, I feel like it's in my control."

6. DISCUSSION

The results of our user study indicate that a system aimed at fostering spatial awareness through increasing the legibility of the environment can enable pedestrians with visual impairments to visit unfamiliar locations with a greater sense of independence, and can further enrich their navigational experience. In particular, the spatial awareness provided by TP3 enables pedestrians with visual impairments to explore their environments and grants them access to information about resources in the environment that they may not otherwise have received. Indeed, it may well be the case that a system designed to provide turn-by-turn directions would have allowed our participants to complete their wayfinding tasks more effectively and more efficiently than they were able to do with TP3. However, we argue that the additional benefits that accrue from allowing users to have greater control over their navigational strategy and from being exposed to spatial information not directly related to a particular task outweigh any reduction in user performance. A promising direction for future work is to seek ways to integrate the best of both approaches—indeed several participants found it hard to keep the task directions in mind while navigating with TP3, indicating that at least a recording mechanism for directions would be helpful, if not a full-blown turn-by-turn directions feature.

6.1 Limitations

As noted earlier, our prototype suffered from usability shortcomings and was not entirely robust, which may have impacted the efficacy of TP3 in this study. It is possible that a more stable prototype would have further improved the experience of participants in our study, and the efficacy of TP3 in both spatial awareness support and wayfinding.

A potential concern remains surrounding the amount of data required to make TP3 useful. Currently, there do not exist extensive lists of POI data for indoor environments, and even outdoor environments are lacking much of the data required for supporting travelers with visual impairments. TP3 addresses this lack by supporting community-generated content and suggesting strategies for seeding the data for particular sites. However, it remains in an area for future work to understand how much the value of TP3 would be affected by the quantity of location data available to the users and where the threshholds lie for impacts on the user experience.

7. CONCLUSION

Our observations from the TP3 user study indicate that providing users with specific types of information about the environment along with tools for accessing it is helpful for supporting general spatial awareness among individuals with visual impairments. This increased spatial awareness is, in turn, helpful for supporting wayfinding in a broad sense for travelers with visual impairments. Further, our participants' experiences with TP3 indicate that, through fostering an increased awareness of the environment, mobile location-based technology can increase the sense of independence for users of such tools and enable them to embark on journeys that they might otherwise avoid.

8. ACKNOWLEDGMENTS

We are grateful to Jim Knox, Royster Harper and Ann Arbor Center for Independent Living for their support. We would also like to thank our participants and all previous members of the Talking Points team (http://talking-points.org/team).

9. REFERENCES

1. Arthur, P. and Passini, R. 1992. *Wayfinding: People, Signs, and Architecture*. McGraw-Hill Ryerson, Toronto.
2. Cheverst, K., Mitchell, K. and Davies, N. 2001. Investigating Context-aware Information Push vs. Information Pull to Tourists. In *Proc. MobileHCI 2001.* ACM, New York, NY, 1-6.
3. Cook B, Buckberry G, Scowcroft I, Mitchell J, Allen T. 2005. Indoor Location Using Trilateration Characteristics, In *Proc. London Communications Symposium*. 147-150.
4. Dahlbäck, N., Jönsson, A., and Ahrenberg, L. 1993. Wizard of Oz studies: why and how. In *Proc. IUI '93*, ACM, New York, NY, 193-200.
5. Gifford, S., Knox, J., James, J., and Prakash, A. 2006. Introduction to the talking points project. In *Proc. ASSETS '06*, ACM, New York, NY, 271-272.
6. Golledge, R.G., Marston, J.R., Loomis, J.M., & Klatzky, R.L. 2004. Stated preferences for components of a personal guidance system for non-visual navigation. *Journal of Vision Impairment and Blindness, 98*, 135-147.
7. Helal, A., Moore, S.E., and Ramachandran, B. 2001. Drishti: An Integrated Navigation System for Visually Impaired and Disabled. In *Proc. ISWC '01*, 149-156.
8. Ishikawa, T., Fujiwara, H., Imai, O., and Okabe, 2008. A. Wayfinding with a GPS-based mobile navigation system: A comparison with maps and direct experience. *Journal of Environmental Psychology 28*, 1, 74–82.
9. Leshed, G., Velden, T., Rieger, O., Kot, B., and Sengers, P. 2008. In-car GPS navigation: engagement with and disengagement from the environment. In *Proc. CHI '08*, ACM, New York, NY, 1675-1684.
10. Lim, H., Kung, L.-C., Hou, J.C., and Luo, H. 2010. Zero-configuration indoor localization over IEEE 802.11 wireless infrastructure. *Wireless Networks 16,* 2, 405–420.
11. Loomis, J.M., Golledge, R.G., Klatzky, R.L., Speigle, J.M., and Tietz, J. 1994. Personal guidance system for the visually impaired. In *Proc. ASSETS '94*, ACM, New York, NY, 85-91.
12. Loomis, J.M., Marston, J.R., Golledge, R.G., and Klatzky, R.L. 2005. Personal guidance system for people with visual impairment: A comparison of spatial displays for route guidance. *Journal of Visual Impairment & Blindness 99*, 4, 219-232.
13. Lynch, K. 1960. *The Image of the City*. The MIT Press, Cambridge.
14. Passini, R. and Proulx, G. 1988. Wayfinding without vision: an experiment with congenitally totally blind people. *Environment and Behavior 20*, 2, 227-252.
15. Passini, R. *Wayfinding in Architecture.* 1984. New York: Van Nostrand Reinhold.
16. Petrie, H., Johnson, V., Strothotte, T., Raab, A., Fritz, S., and Michel, R. 1996. MoBIC: Designing a travel aid for blind and elderly people. *Journal of Navigation 49*, 45-52.
17. Pielot, M. and Boll, S. 2010. Tactile Wayfinder: comparison of tactile waypoint navigation with commercial pedestrian navigation systems. In *Proc. Pervasive 2010*, Springer-Verlag, Berlin, Heidelberg. 76-93.
18. Pressl, B. and Wieser, M. 2006. A computer-based navigation system tailored to the needs of blind people. In *Proc. ICCHP 2006*, Springer-Verlag, Berlin, Heidelberg, 1280-1286.
19. Quiñones, P., Greene, T.C., Yang, R., and Newman, M.W. 2011. Supporting Visually Impaired Navigation: A Needs-finding Study. In *Ext. Abstracts of CHI '11,* ACM, New York, NY, 1645-1650.
20. Sanchez, J.H., Aguayo, F.A., and Hassler, T.M. 2007. Independent Outdoor Mobility for the Blind. *Virtual Rehabilitation,* 114-120.
21. Stewart, J., Bauman, S., Escobar, M., Hilden, J., Bihani, K., and Newman, M.W. 2008. Accessible contextual information for urban orientation. In *Proc. Ubicomp '08*, ACM, New York, NY, 332-335.
22. Viégas, F.B., Wattenberg, M., and McKeon, M.M. 2007. The hidden order of Wikipedia. In *Proc. OCSC '07*, Springer-Verlag, Berlin, Heidelberg, 445–454.
23. Völkel, T., Kühn, R., and Weber, G. Mobility Impaired Pedestrians Are Not Cars: Requirements for the Annotation of Geographical Data. In *Proc. ICCHP '08*, Springer-Verlag, Berlin, Heidelberg, 1085-1092.
24. Walker, B.N. and Lindsay, J. 2006. Navigation performance with a virtual auditory display: Effects of beacon sound, capture radius, and practice. *Human Factors*, *48*, 2, 265-278.