SpaceSense: Representing Geographical Information to Visually Impaired People Using Spatial Tactile Feedback

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ABSTRACT

Learning an environment can be challenging for people with visual impairments. Braille maps allow their users to understand the spatial relationship between a set of places. However, physical Braille maps are often costly, may not always cover an area of interest with sufficient detail, and might not present up-to-date information. We built a handheld system for representing geographical information called SpaceSense, which includes custom spatial tactile feedback hardware—multiple vibration motors attached to different locations on a mobile touch-screen device. It offers high-level information about the distance and direction towards a destination and bookmarked places through vibrotactile feedback to help the user maintain the spatial relationships between these points. SpaceSense also adapts a summarization technique for online user reviews of public and commercial venues. Our user study shows that participants could build and maintain the spatial relationships between places on a map more accurately with SpaceSense compared to a system without spatial tactile feedback. They pointed specifically to having spatial tactile feedback as the contributing factor in successfully building and maintaining their mental map.

Author Keywords

Vibrotactile feedback; handheld devices; touch screens; geographical information representation; users with visual impairments; assistive technology.

ACM Classification Keywords

H.5.2 [Information Interfaces and presentation]: User Interfaces – *Haptic I/O, Voice I/O.*

General Terms

Human Factors

INTRODUCTION

Acquiring knowledge about an environment can be challenging for people with visual impairments. They often need support by sighted people to understand what is in the environment, where venues are positioned, and their spatial relationship with each other. They sometimes also need to physically navigate an environment multiple times before they can develop a familiarity with the environment. Although such activities can help visually impaired people increase their independence and confidence in their navigation, burdens associated with these activities often discourage them to explore and learn an environment [33].

Braille maps (*a.k.a.* tactile maps) are an effective way for visually impaired people to develop an understanding of the spatial relationships between a set of places in addition to identifying directions between them [3, 7]. Prior work has shown that Braille maps can help visually impaired people prepare for their future trips to an area [3, 12]. But, they use physical materials that are often costly to produce, may not always cover an area of interest with sufficient detail, and might not present updated information [26].

We explore a way of representing geographical information to visually impaired users on a handheld device. We chose this form factor because mobile devices have been interwoven into their daily life (*e.g.*, calling someone for help, and sending an email) [12]. Thus, a map application on mobile devices can provide users with easy access to geographical information and encourage their spatial learning about the area of interest. Our investigation includes the use of two feedback channels—auditory (speech) feedback and tactile feedback—to present places of interest, provide detailed information about those locations, and present routes to those points.

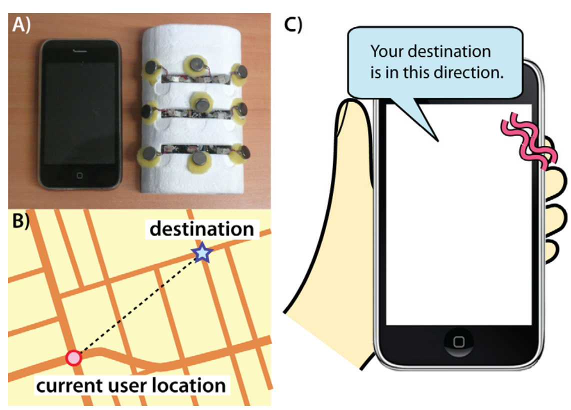

Figure 1. A) The spatial tactile feedback hardware. Nine vibration motors are embedded in the sleeve that fits to an iPhone; B) An example geographical information being browsed by the user (with the destination north-east from the user's location); C) Spatial tactile feedback conveys the general direction towards the destination.

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The main contribution of this work is the design and evaluation of a system that helps people learn directions to a location and its spatial relationships with other locations on a map through use of spatial tactile feedback to represent geographical information. Our map system, SpaceSense, is a mobile application for touch-screen devices enhanced with custom spatial tactile feedback hardware. This hardware embeds nine vibration motors aligned in a 3 × 3 grid (Figure 1A), and can be used to generate vibrotactile feedback in different positions of the user's palm and fingers holding the device. Through this spatial tactile feedback, SpaceSense offers high-level information about the direction towards the destination when the user browses route information (Figure 1B and 1C). Furthermore, SpaceSense provides directional information towards other locations that the user may know or like through vibrotactile feedback. In this manner, SpaceSpace can help visually impaired users maintain high-level spatial relationships between multiple locations. SpaceSense also adapts the Review Spotlight system [35] for summarizing online user reviews about nearby locations. It reads out the most frequently-used adjective-noun word pairs extracted from online reviews to offer an overview of what people often mention about a specific place. Thus, the user can obtain information about a location before deciding whether she wants to further learn routes to it and its spatial relationships to other locations.

Through a user study with twelve visually impaired users, we learned that participants were able to build and maintain the spatial relationship between four places more accurately with SpaceSense than a system without spatial tactile feedback. Participants also explicitly mentioned benefits with having spatial tactile feedback in building and maintaining their mental map. Additionally, the Review Spotlight presentation through the auditory channel was received positively by the participants because of its succinct presentation about a location.

RELATED WORK

Braille maps have been recognized as an effective means of learning spatial relationships between multiple objects for people with visual impairments [3]. Herman *et al.* [8] found that visually impaired people can indicate the locations of objects in a space fairly accurately after they were exposed to a miniaturized version of the space layout. However, these maps are physical, and their production cost is often considerable. These maps may sometimes not have sufficient detail or updated information of the space. Digital maps can address these issues; in this section, we review computer systems to support learning spatial relationships between multiple objects for visually impaired people.

Interfaces for Map Exploration

Auditory feedback is often used to make map information accessible to people with visually impairments [9, 27, 37, 39]. To allow them to explore and learn geographical information, touch-based interaction can be integrated with such audible map systems. For example, the NOMAD system [23] uses a touchpad placed under a paper Braille map to detect which part of the map the user is contacting. When the user touches an area on the map that contains information, the system generates speech feedback to describe the user's contact point. Jacobson [11] developed a similar system which replaces the use of static Braille maps with dynamically generated maps. It provides auditory feedback (either sound or speech) to describe what the user is touching and its surrounding content. Jacobson validated that visually impaired users could reconstruct map information after they used such a system. Parente and Bishop [22] showed that vibrotactile feedback when combined with speech and non-speech audio feedback helps visually impaired users discover the boundaries of mapped elements (*e.g.*, boundaries of states in the United States map). Lahav and Mioduser [16] showed that a virtual environment system, which combines speech audio and force feedback through a joystick, enabled visually impaired users to build a cognitive map of an indoor location, and successfully navigate the corresponding physical space based on this cognitive map.

Some map systems describe path information (*e.g.*, the length or shape of a street). Google's Intersection Explorer is a hand-held application which allows the user to drag her finger on the screen to explore walkable paths that a person can take from any intersection [10]. With non-speech sound cues, Timbremap [30] helps users trace routes on a mobile device and learn geometrical patterns of walkable path segments. Its evaluation showed that visually impaired users could learn non-trivial geometries using only touch and simple audio cues. Similarly, Crossan and Brewster demonstrated that the combination of force feedback and sound feedback can also facilitate the learning of trajectories [6].

The main focus of SpaceSense is to provide visually impaired users with a high-level understanding of the spatial relationships between multiple locations instead of the exact shape of a street or a building. Thus, our system can complement these existing systems by facilitating the acquisition of route information and high-level spatial information for multiple locations. Kane *et al.* [13] developed three techniques which allow visually impaired users to identify the target locations displayed on a touch-sensitive tabletop. Their techniques can be used for learning spatial relationships between multiple locations, but may not be appropriate for devices with a small form factor. Our exploration also examines the effect of vibrotactile feedback in learning spatial relationships.

Interfaces for Navigation and Wayfinding

Another opportunity for people with visual impairments to explore and learn about places is *in situ* during navigation. There are a number of commercially available systems [28, 31, 32, 33] and open-source systems [17] that provide speech navigation instructions and information about points of interest. Azenkot *et al.*'s system [2], ChattyEnvironment [5] and Talking Points [29] are examples of location-aware navigation systems which help the user learn nearby places.

Past research also has explored ways to provide visually impaired users with trajectory information for wayfinding. Marston *et al.* [18] showed that visually impaired users can navigate an environment faster using a continuously-generated beeping 3D sound which encodes the direction to the next waypoint than Talking Signs [31] (using sound feedback when the user pointed the device towards the next waypoint). Wilson *et al.* [38] showed that the user can successfully learn information about her environment (*e.g.*, obstacles in the way) encoded as different dimensions of the sound (*e.g.*, a sound type, pitch, and rhythm) or time-compressed speech.

Tactile feedback has also been used to aid visually impaired people in wayfinding. Ross and Blasch [25] compared speech audio, non-speech audio, and tapping haptic feedback to indicate the direction in which a user should walk. They found that visually impaired users overall performed navigation tasks fastest and with fewest errors using the haptic interface, with non-speech audio coming in close second. Zelek *et al.* [39] showed that a haptic glove, which conveys the locations of obstacles in an environment through vibrations on different fingers, could help users identify where they can walk. Amemiya and Sugiyama [1] developed a mobile device using force feedback to provide the user with a sensation of being pulled towards the destination by the device, allowing her to navigate at her normal walking speed.

These projects aim to help visually impaired users learn their environment *in situ* and reinforce their cognitive map of the geographic area. SpaceSense attempts to provide an additional means which helps the user prepare for future trips (*i.e.,* prior to physically visiting a space) by supporting the learning of map information and spatial relationships of objects using tactile feedback which differentiates it from prior work.

THE SPACESENSE SYSTEM

SpaceSense is a map application that runs on a handheld touch-screen device (an iPhone in our current prototype) enhanced by our custom spatial tactile feedback system. Our motivation for choosing a mobile touch-screen device is that it allows for taps and flick gestures—interactions that are easy for visually impaired users to perform [14, 19]. In the remainder of this section, we describe our hardware for producing spatial tactile feedback, and the interactions supported by SpaceSense: identifying locations, learning place details, and learning directions.

Spatial Tactile Feedback Hardware

Figure 1A shows the hardware for our spatial tactile feedback system. Similar to SemFeel [36], we built a special case that embeds vibration motors on the backside of the mobile device. However, our prototype uses nine vibration motors aligned in a 3 × 3 grid. Any two of the motors are separated with a gap of at least 2 cm, and each motor vibrates at 200 Hz when activated. The placement of the motors is partly based on psychological understanding that it is difficult to distinguish two vibration sources located closer than 1 cm [21], but is adopted primarily so that the system can have greater spatial granularity than the SemFeel prototype [36]. SpaceSense uses all the vibration motors except the one located in the center.

For audio feedback, SpaceSense uses the FliteTTS[1] package to read out information through a synthesized voice. We use this package instead of the VoiceOver functionality already built in some of the iPhone devices because we wanted the ability to precisely tune the timing of the speech feedback.

Interactions

Identifying Locations

SpaceSense allows the user to select places of interest from a pre-defined list of categories ("restaurant," "café", "bar," "hotel," "attraction," and "bank" in the current prototype system). The system retrieves up to 20 locations (using Yelp API[2]) sorted by distance within a 2 km radius centered on the user's current simulated location. After the user selects a category, SpaceSense begins to present information about each location, starting with the closest.

SpaceSense offers spatial information in an exo-centric manner similar to when a person views at a map. It reads the name and street address of each place, and uses spatial tactile feedback to indicate the place's distance and cardinal direction. For instance, if the place is to the west of a referenced location (*e.g.,* the hotel where the user may be staying on an upcoming trip), the left side of the device vibrates (north is always set to the top of the device). We designed the current prototype to provide vibration at four different strength levels (100%, 80%, 60%, and 30% strength output of a vibration motor) to represent the distance (below 200 m, below 500 m, below 1 km, or farther than 1 km, respectively).

The user can perform an upward or downward flick gesture to navigate the category list and subsequent location list. The user can also repeat the current item by double-tapping the screen. We use a double tap gesture because the user is less likely to perform a double tap accidentally than a single tap. The user can select a category by rightward flick gestures. These gestures are also used for navigation and selection consistently throughout the system.

Learning Place Details

After the user selects a location, SpaceSense presents her with general information about the location, including the name, address, and phone number. The user can navigate this information using upward or downward flick gestures.

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[1] https://bitbucket.org/sfoster/iphone-tts
[2] http://www.yelp.com/developers/documentation/v2/overview

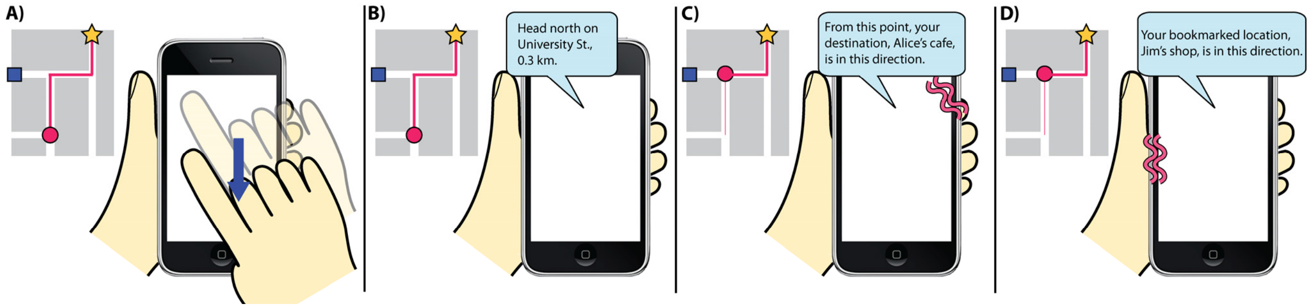

Figure 2. Interactions supported by SpaceSense. The circle, star and square in the map represent the user's simulated location, destination, and bookmarked location, respectively: A) The user performs a downward flick gesture to get the next instruction; B) SpaceSense reads out the street name and orientation; C) Spatial tactile feedback conveys the high-level direction towards the destination. In this example, the user feels vibration from the top-right side of the device because the destination is located to north-east from the user's simulated location; D) Spatial tactile feedback is also provided for the bookmarked location.

Item	Example
Name	Moonbean Coffee Shop
Address	30 St. Andrew St.
Phone	416 595 0327
Distance	0.6 km
Review words	Soy latte, friendly staff, back patio, good coffee, front patio, great coffee, little café, great person, great place, reasonable price.

Table 1. An example of place details provided by SpaceSense.

SpaceSense also offers an overview of what people mention about a specific public or commercial location on online review Websites (such as Yelp.com). It uses the adjective-noun word pairs extracted from the original review text that Review Spotlight [35] normally presents in a visual interface. Instead of visually displaying, SpaceSense reads out the ten most frequently mentioned adjective-noun word pairs through the speech feedback instead of the original review text ("review words" in Table 1).

The user can add the location to their bookmark list by using a two-finger rightward flick gesture on the touch screen. This bookmark functionality allows the user to save and quickly access places that she likes.

Learning Directions

Finally, SpaceSense gives the user directions to a location. The user can perform a rightward flick gesture to select a location while she is browsing the details of that location (as described in the previous section). The system then begins to provide step-by-step walking instructions (using speech feedback) obtained through the Google Directions API[3]. The system presents each step of the instructions in the cardinal directions along with its walking distance (*e.g.*, "head north on University Ave., 0.3 km") one at a time (Figure 2B). SpaceSense also offers audio descriptions about the intersection at which a simulated performance of the previous step would put the user (*e.g.*, "You are now at University Ave. and College St.").

[3] https://code.google.com/apis/maps/documentation/directions/

The system conveys the distance and direction to the destination through spatial tactile feedback. For example, if the destination is located to the north-east from the current intersection, the top-right side of the device will vibrate (Figure 2C). Spatial tactile feedback is provided every time the system presents an intersection. In this manner, SpaceSense shows the user how the relationships of the destination and other locations change through the simulated movements of the referenced location similar to when reading a map.

The interactions in this mode are consistent to other modes in SpaceSense. The user can perform upward or downward flick gestures to navigate the route instructions (upward for moving to the previous instruction and downward for moving to the next instruction). The user can also double-tap on the screen to repeat the current instruction.

SpaceSense also provides spatial tactile feedback about nearby bookmarked locations. It will vibrate in the direction of a bookmarked location near the simulated route while the speech feedback indicates the location's name. For example, in Figure 2D, the system will vibrate on the left side of the device to indicate the bookmarked location. We designed this feature to help the user build and maintain spatial relationships between multiple places of interest.

EVALUATION

The target usage scenario of SpaceSense is when the user searches for locations that support a particular activity before she travels outside. Thus, a laboratory study reflects this scenario better than a study in which participants are walking on the street. Our laboratory study consisted of two parts to independently evaluate how well SpaceSense can support this scenario in a holistic manner: 1) user feedback on the overall system; and 2) an evaluation of the system's effect on the learning of routes and the spatial relationships between multiple locations. All conversations between the investigator and participants were audiotaped and transcribed for the analysis.

Participants

We recruited twelve visually impaired users (4 male and 8 female; P1–P12). The level of their visual impairments

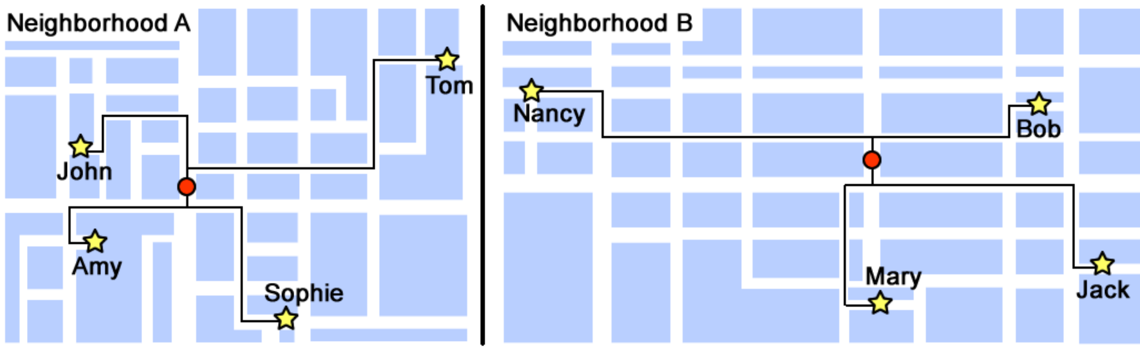

Figure 3. The two neighborhoods with four hypothetical locations used in the user study, and routes to those locations from a given starting point.

varied: 10 of them were blind, and 2 had low vision. Before the experiment, we asked them to describe familiar areas in the city, and none of them expressed a significant familiarity of the areas used in this experiment. Additionally, we asked participants about their familiarity with the locations used in the second part of the study; none was familiar with either location as well. The entire study took on average 80 minutes in total for participants to complete. Participants were compensated with $50 for their participation after the study.

Part A: User Feedback on the Overall System Design

We demonstrated the full system to participants and allowed them to interact with the system. We then interviewed participants to examine SpaceSense from a usability perspective. We encourage them to provide feedback on any aspect of the system by asking them to comment on the design of the gestures, the different features of the system, and potential use scenarios.

We also examined whether an audio adaptation of Review Spotlight [35] could be useful in providing visually impaired users with descriptive information about a public or commercial place. We prepared two places (a restaurant and a café) for this task. For each location, we prepared two presentations for reviews: *ReviewSpotlight* (reading out adjective-noun word pairs most frequently mentioned in Yelp.com) and *ReviewHighlights* (reading out sentences with approximately 50 words extracted from the review text, provided in Google Map). Participants were asked to express their opinions about both presentations.

Part B: Learning Routes and Spatial Relationships

To examine whether spatial tactile feedback can help visually impaired people learn routes and develop a high-level understanding of the spatial relationships between multiple locations, we asked participants to learn the directions to four locations from the same neighborhood, one at a time (Figure 3). For each destination, another location from the same neighborhood was set in the bookmark list beforehand; thus, each instruction provided to participants would always include directional information towards the destination and one other place as explained in the Learning Directions section. The combination of the destinations and bookmarked places

Neighborhood A		Neighborhood B	
Destination	Bookmark	Destination	Bookmark
Amy	John	Bob	Mary
John	Tom	Mary	Nancy
Tom	Sophie	Nancy	Jack
Sophie	Amy	Jack	Bob

Table 2. The combinations of the destinations and bookmarked places used in the study.

used in the study was determined as shown in Table 2. This setup allowed us to examine how well our system design could help participants learn spatial relationship between multiple locations.

We selected two neighborhoods in a North American city with an area of approximately 4 km^2. For each neighborhood, we set the starting point near the center, and selected four locations which were on average 770 m from the starting point, and required three turns to reach. We labeled these locations as the stores of four hypothetical persons (Figure 3).

Participants were allowed to navigate the route instructions freely by using flick gestures or double-taps (explained in the Learning Directions section) until they felt comfortable with the route. The experimenter helped the participants when the system did not register gestures or taps accurately, but did not provide any information about the route information. The participants held the mobile device with their non-dominant hand, and used the dominant hand to interact with the device.

After the participants went through the directions to one location, they were asked to reproduce the route with acrylic pieces and indicate the locations of the destination and the bookmarked place (Figure 4). This route reconstruction is a common task used to probe the visually impaired user's understanding of spatial knowledge [15], and was used to evaluate the effects of the two feedback types on the participant's understanding of the route information. We prepared thin rectangular pieces with four different lengths for streets (3 cm, 6 cm, 9 cm, and 12 cm long for loosely representing from very short to very long street segments), L-shape pieces for corners, and circles for the destination and the bookmarked place. The participants were allowed to use any piece to compose a route. But we instructed that they could compose all routes without using

Figure 4. A participant creating a route with acrylic pieces after she has learned route instructions from the system.

multiple rectangular pieces to make a longer street. The experimenter did not correct the participant's route composition at any point.

After participants were exposed to the directions to all the locations and composed routes, the experimenter asked them to draw locations of all the places—indicating their perception of the positions of the four locations—on a blank sheet of paper with a blue marker (Figure 5). This drawing was used to examine the effects of the two feedback types on learning the spatial relationships between the four locations. The experimenter made annotations for later analysis, but did not make any correction even if the spatial relationships among the four locations indicated by participants were incorrect. We simplified the drawing requirements; thus, it is unlikely that individual drawing skills affected the results.

For this part of the experiment, we set up two conditions to compare: *Tactile* (the interface design explained in the previous sections) and *Audio* (an interface which provided all information including the direction and distance for each location through only speech feedback). In the *Audio* condition, the system read out the direction and distance towards the destination and bookmarked location (*e.g.*,"Your destination, Amy's café, is to north-east, 0.5 km"). We tuned the speed of the speech feedback at a slower rate than the iPhone VoiceOver so that participants could follow the information provided by the system more easily. The presentation order of the two interface conditions and the maps were counter-balanced across the participants. We fixed the combinations of destinations and bookmarked locations (Table 2), but we randomized their presentation order for each participant. At the beginning of the task, we provided all participants with training and practice using each interface until they were comfortable with the procedure.

PART A RESULTS

All participants could navigate the route instructions and understand the information presented through the spatial tactile feedback hardware after receiving the explanation from the investigator. None of them experienced difficulty performing the flick or double-tap gesture.

Participants commented that they would use SpaceSense before they need to visit an unfamiliar area. For example, P9 explained that she could develop independence and

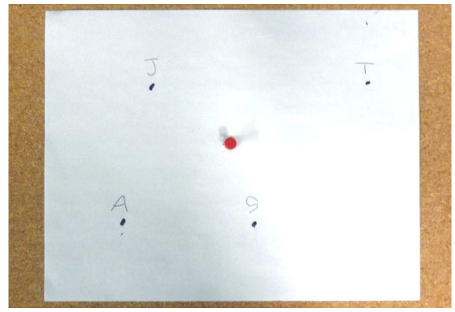

Figure 5. The dots a participant drew after learning four places in Neighborhood A with our SpaceSense system's tactile interface. The red pin at the center of the paper indicates the starting point.

confidence with navigation enabled by SpaceSense's support for pre-trip map exploration.

> *I don't really go outside by myself, but I think [SpaceSense] could give a little bit more independence. You can ask people when you are on the street, but it would be neat to do it by yourself [ahead of time]. I don't walk very far at this point, but it would give me more confidence.* [P9]

We found that all of the participants preferred *ReviewSpotlight* over *ReviewHighlight* for presenting information about public and commercial locations. They liked its succinct presentation. They also liked that the *ReviewSpotlight* presentation summarized all reviews instead of presenting one particular review. Some explicitly commented that the *ReviewSpotlight* presentation was easier to follow than *ReviewHighlights*.

> *The first one (ReviewSpotlight) is obviously a better one, much much better. It's clear in a sense, because of its form. The other one (ReviewHighlight) is more jumpy… Your brain has to sort out… It stops randomly too much, and is missing data. It (ReviewHighlight) would be something you have to replay.* [P3]

PART B RESULTS

We next analyzed data on participants' learning of routes and spatial relationships between four places in a map and acquisition of information about places. We report task completion time, accuracy, and comments from participants.

Task Completion Time

Participants used the system on average for 201 seconds to learn the route instructions (*InstructionTime*) and 95 seconds to reproduce a route with acrylic pieces (*CompositionTime*). Table 3 shows *InstructionTime* and *CompositionTime* across the conditions and neighborhoods. Participants were exposed to both conditions but with different neighborhoods. Thus, we ran a two-way mixed ANOVA on both time measures for the conditions and neighborhoods. It did not reveal a significant difference on either *IntructionTime* (Condition: $F_{(1,10)}$=0.04, Neighborhood: $F_{(1,10)}$=0.29, Condition × Neighborhood: $F_{(1,10)}$=0.26, p>.05 for all) or *CompositionTime* (Condition:

Neighborhood	*InstructionTime* A	B	*CompositionTime* A	B
Tactile	*203* (64)	*195* (136)	*86* (16)	*97* (32)
Audio	*188* (99)	*220* (83)	*103* (45)	*95* (28)

Mean (SD)

Table 3. The time participants spent in learning the route instructions (*InstructionTime*) and reproducing a route with acrylic pieces (*CompositionTime*).

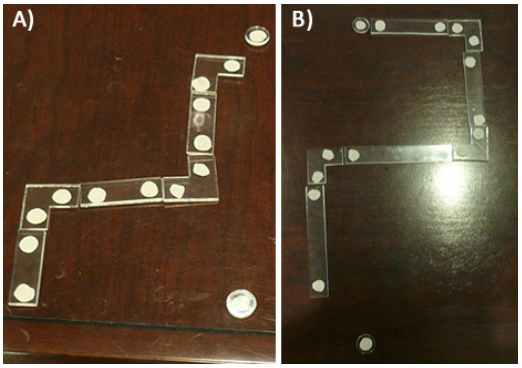

Figure 6. Route compositions to Tom with Sophie as the bookmarked place in Neighborhood A made by two different participants: A) A composition close to the correct route; B) An incorrect composition.

$F_{(1,10)}$=1.18, Neighborhood: $F_{(1,10)}$=0.06, Condition × Neighborhood: $F_{(1,10)}$=0.51, p>.05 for all).

Route Accuracy

Figure 6 shows examples of the routes created by participants. We adapted an evaluation approach used by Passini *et al*. [24] to analyze the route compositions. We used the following metrics:

- *NumberElementsError*: The number of unnecessary acrylic pieces that participants used to recreate a route. The correct number of pieces was always seven because there were four different streets and three corners/turns in each route.
- *FormElementsError*: The Levenshtein distance (the minimum number of operations required to transform one sequence into the other) between the participant's route composition and the correct route composition.
- *PositionError*: The number of incorrect orientations of the L-shape pieces.
- *PlacementError*: The number of street blocks used with the incorrect length.

We added three metrics to measure the accuracy of the positions of the destination and bookmarked place:

- *DestinationDistanceError*: The absolute difference of the straight line distance between the starting point and destination from the one in the correct route composition.
- *BookmarkDistanceError*: The absolute difference of the straight line distance between the starting point and bookmarked place from the one in the correct route composition.

Condition	Error Number	Form	Position	Placement
Tactile	*0.80* (1.27)	*0.83* (1.28)	*0.77* (1.18)	*2.75* (1.16)
Audio	*0.83* (1.18)	*0.88* (1.18)	*0.54* (0.93)	*2.79* (1.13)
t value	$t_{93.4}$=0.16	$t_{93.4}$=0.16	$t_{89.4}$=1.05	$t_{93.9}$=0.18

Condition	DestDist	BookDist	PlaceAngle
Tactile	*2.11* (1.47)	*2.67* (1.90)	*53.0* (35.8)
Audio	*2.25* (1.82)	*2.55* (1.73)	*46.7* (33.8)
t value	$t_{89.3}$=0.39	$t_{93.2}$=0.33	$t_{84.4}$=1.48

Mean (SD)

Table 4. The seven error metrics measured on the route composition. Welch's t-tests did not show a significant difference in any of the metrics at the 95% confidence level.

- *PlaceAngleError*: The absolute difference of the angle between the edge connecting the starting point and destination and the one connecting the starting point and the bookmarked place from the one in the correct route composition.

Two of the researchers independently estimated the values for these three metrics for each route composition. We then used the average value for the analysis.

Table 4 illustrates the error metrics for the route composition. Because each participant was exposed to a different map for each condition, we used unpaired Welch's t-tests for our statistical analysis. Our analysis did not show any significant difference between the *Tactile* and *Audio* conditions at the 95% confidence level.

Route instructions were given through the speech feedback in both conditions. Therefore, it is sensible that we did not observe large differences in the accuracy of the route compositions. A difference between the two conditions could appear in their understanding of spatial relationships between the four places in a map. We, thus, analyzed the drawings of the four places provided by the participants.

Drawn Places Accuracy

For the place drawings (Figure 5), we used different neighborhoods for the two feedback conditions. Therefore, comparing and determining the accuracy of the two drawings by each participant was not straightforward. We decided to use subjective ratings to evaluate the spatial relationship between any two of the places from the starting point with three levels of correctness ratings:

2: Very close to the correct placement of the two places,

1: Neither completely correct nor incorrect, and

0: Not correct.

For the example shown in Figure 5, the rating between S and T (Sophie and Tom) was 2. The rating between A and S (Amy and Sophie) was 1 because the orientation between the two places is not correct but their relative positions from the starting point are close to the correct answer.

With several randomly chosen drawings, we confirmed that this rating scheme could represent the accuracy of the drawings. Two of the researchers then independently rated all the drawings. They only knew which neighborhood each drawing was for. To measure the inter-rater reliability of

Neighborhood	Places	*Tactile*	*Audio*
A	Amy-John	*0.91* (0.73)	*0.50* (0.76)
	Amy-Sophie	*1.00* (0.58)	*0.67* (0.47)
	Amy-Tom	*1.08* (0.18)	*1.00* (0.81)
	John-Sophie	*0.83* (0.68)	*0.83* (0.89)
	John-Tom	*0.75* (0.38)	*1.00* (0.82)
	Sophie-Tom	*1.50* (0.50)	*0.75* (0.69)
	Average	***1.01* (0.59)**	***0.79* (0.78)**
B	Bob-Jack	*0.16* (0.37)	*0.58* (0.83)
	Bob-Mary	*0.50* (0.76)	*0.33* (0.55)
	Bob-Nancy	*0.58* (0.73)	*0.41* (0.60)
	Jack-Mary	*0.33* (0.47)	*0.33* (0.55)
	Jack-Nancy	*0.50* (0.76)	*0.17* (0.37)
	Mary-Nancy	*1.33* (0.74)	*0.25* (0.38)
	Average	***0.57* (0.75)**	***0.35* (0.59)**

Mean (SD)

Table 5. The ratings for all the combinations of two places in each map across the two conditions.

this ordinal scale, we calculated the Cohen's κ with the squared weighting [4]. In this calculation, the disagreements of the ratings were weighted according to their squared distance from perfect agreement. As a result, the weighted Cohen's κ was .92 (95% CI: [.87, .96]), showing a strong agreement. The average rating was used to determine the accuracy of each drawing.

Table 5 shows the ratings for the correctness of the spatial relationship of all possible pairs of places in each map across the two conditions. A Mann-Whitney test found a significant difference in the correctness ratings between the *Tactile* and *Audio* conditions (Z=1.96, p<.05, the effect size r=0.23). The drawings created by participants after they used SpaceSense were more accurate than those which provided map information using the speech feedback solely. The main difference was in what direction participants perceived the locations to be from one location to another.

Results also indicate that Neighborhood B was seemingly harder than Neighborhood A for participants to learn. But regardless of the neighborhoods, participants understood the spatial relationships between locations better with the SpaceSense system than the *Audio* condition.

User Feedback

Overall, as one participant mentioned, the system provided information in a way that was very similar to what she experienced when orientation and mobility specialists taught her routes.

> *I like that the coordinate is actually on my hand… When I first started to learn how to do routes, my instructor would draw maps on my hand and use the exact same points as coordinates like the vibration system uses (for the directional information).* [P5]

Participants expressed that SpaceSense allowed them to develop a rich cognitive map of an area in a way that is similar to and possibly even better than with Braille maps.

> *[The vibration] was helpful because it gave me a very visual sense of where things should be… Instead of having to have someone label and make the map tactile, [the system] did that for me. And instead of having to take out a piece of paper with streets and stuff labeled and then have to look and see "ok this is south-west," for example, the vibration gave me that visual sense.* [P5]

Most of the participants noted that the strength of the SpaceSense system lies in its use of both the auditory and tactile channels. Particularly, they liked having directional information provided through the tactile channel.

> *It gave me information about the direction more quickly. Because it takes more time to say "north-east" or "south-west." But feeling the vibration in your hand gets the information to my brain more quickly.* [P2]

Participants felt that they were able to develop a mental map of the locations more quickly with SpaceSense than the system using only speech feedback. The tactile feedback provided in each step of the directions helped to confirm their mental map.

> *I could anticipate the next direction based on the vibration of the locations. It took longer [to do the same thing] with audio... I sort of knew which direction was next because the vibration was pointing me to a particular direction. So I could anticipate the audio instruction. I could anticipate that because of the vibration.* [P3]

In comparison, when only given audio interface, the participants described needing to work harder to construct a cognitive map.

> *I had to abstractly think where we are going, and put the information provided by the system together. It is a little easier to put together in the map with the tactile stimulation with the combination of the sound as supposed to [the audio condition].* [P4]

DISCUSSIONS

Information Overload through the Audio Channel

We found that the place drawings by the participants were more accurate in the *Tactile* than the *Audio* condition. The major reason participants found benefits with having a separate feedback channel for directional information was that spatial tactile feedback enhanced their memory of the spatial relationships between locations. They explicitly mentioned that the information was overwhelming in the *Audio* condition. P4 pointed out that it was difficult for her to maintain all the information in her mind.

> *(In the Audio condition), I had to listen to the audio over and over just to get the direction, right or left. And I had to keep track of Mary's store, Bob's store, the two names of the people. And then I had to keep track of the directions to get there.* [P4]

But participants explained that receiving directional information over the tactile channel lessened the need to concentrate heavily on the speech feedback. P4 explained this as follows.

> *With the tactile stimuli, you get the directions in your hand. So you don't have to worry (about the directions) because you can feel it. So you take it away from your memory. And now you just focus on how to get there.* [P4]

Their subjective impressions were corroborated by the difference in their drawing of spatial relationships between four locations across the two conditions. Thus, we conclude that spatial tactile feedback can help participants understand spatial relationships between multiple locations.

Errors and Limitations with Learned Routes and Spatial Relationships

The accuracy of the route and spatial relationships between places was not high. One reason might be that participants still often had to process information provided through the speech feedback even while the spatial tactile feedback provided the directional information. Further research is necessary to understand what an effective presentation of geographical information would be to support visually impaired people to gain accurate route information and cognitive map of multiple locations.

The current SpaceSense system only provides high-level spatial relationships between locations and covers straight streets. When visually impaired users actually navigate space later, they may also need other information, such as the shape of a street or intersection. We believe that integration with a system like Timbremap [30] would enable users to gain such information. Future work includes extending SpaceSense to support the user's acquisition of both high-level and low-level geographical information.

Succinct Presentations about Places

The audio adaptation of Review Spotlight was received positively by the participants mainly because of its succinct presentation of reviews. This is in line with the findings reported in [35], but our study confirms that the Review Spotlight presentation can benefit visually impaired users as well. However, as participants indicated, they may want to access to portions of the original review text to gain more detailed information. This was discussed in the original Review Spotlight work, which incorporates a hyperlink on the adjective-noun word pair to the sentences from which the clicked word pair was extracted [35]. A faithful adaptation of the Review Spotlight system is out of the scope of this work; however, future work should investigate how an audio-based system can effectively support both a quick overview and exploration of details in online user reviews through the speech feedback.

STUDY LIMITATIONS

There are several limitations to mention in this study. Our user study included only four places in one neighborhood. During the presentation of route instructions, only two places were presented through the spatial tactile feedback (the destination and bookmarked place). Future work needs to investigate how the number of places in the space and the number of places presented in the route instructions can affect people's learning of spatial relationships.

There are several aspects of the system which were not covered in this paper. For example, due to the large difference in the number of congenitally and after-birth blind participants, we did not examine the effect of this difference in learning spatial relationships. Our current implementation of SpaceSense uses the exo-centric presentation of directions. But the ego-centric presentation can benefit users better in some cases (*e.g.*, while the user is navigating the space physically). Our study shows that participants were able to learn routes and the spatial relationship between places through an exo-centric presentation of the map information similar to when a person reads a map before visiting a location; further research is necessary to investigate how to best present the spatial relationship of locations through a system like SpaceSense while the user is navigating *in situ*.

CONCLUSION

We developed SpaceSense, a handheld system using spatial tactile feedback to help visually impaired people acquire details about places, learn the directions to a place, and understand high-level spatial relationships between multiple locations. Our user study showed that participants could maintain spatial relationships between four places on a map more accurately when directional information was also presented using spatial tactile feedback than only speech feedback. We also found that the Review Spotlight presentation through the auditory channel was received positively by the participants.

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