Feasibility of Using Haptic Directions through Maps with a Tablet and Smart Watch for People who are Blind and Visually Impaired

William Grussenmeyer
Department of Computer Science and Engineering,
University of Nevada, Reno
Reno, NV, USA
wgrussenmeyer@nevada.unr.edu

Jesel Garcia
Department of Psychology,
University of Nevada, Reno
Reno, NV, USA
jeselg@nevada.unr.edu

Fang Jiang
Department of Psychology,
University of Nevada, Reno
Reno, NV, USA
fangj@unr.edu

ABSTRACT
In order to navigate through the world, people who are blind and visually impaired typically use maps through either textual directions or tactile printouts. However, visual maps on a touchscreen are not accessible to this population. Two prototypes were designed to test users' ability to trace graphical lines and directions through maps on a touchscreen using haptic feedback from an Android smart watch and tablet. With the first prototype, we show that blind and visually impaired users had lower threshold than sighted users for determining the distance between two lines on a touchscreen, suggesting their enhanced ability to form representations of spatial distance from tactile vibrational cues. With the second prototype, we show that it is feasible for blind and visually impaired users to follow directions through graphical maps based on vibrational cues. We believe these results show that our prototypes have the potential to be effective in real-world applications.

ACM Classification Keywords
K.4.2 [Computers and Society]:: Social Issues-Assistive technology for persons with disabilities.

Author Keywords
Touchscreen; wearable computing; accessibility; visually impaired; blind; haptic feedback.

INTRODUCTION
According to the World Health Organization, there are 285 million people with low vision and blindness worldwide [7]. Graphical maps displayed on touchscreens and computer screens are inaccessible to this population. In order to address this inaccessibility, textual descriptions for directions through a map are provided using automation such as Google maps or constructed by hand by a mobility trainer. Another solution is to provide tactile maps which are typically made by hand and printed with a special printer. Because they are hand-made by a sighted person in a time consuming manner and require a special printer which is expensive, people who are blind and visually impaired generally do not have access to these maps as much as they have to textual descriptions. A non-visual, cheap, off-the-shelf system using a touchscreen would allow access to many different maps for the blind and visually impaired without the need of human intervention.

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This research provides the following contributions: (1) a prototype with two cheap, off-the-shelf devices (a smart watch and a tablet) to determine distances between vibrating lines; (2) a comparative user study with this prototype between blind and sighted individuals that shows blind users have a better ability to determine distances through vibrational feedback from two devices; (3) a second prototype that uses more complex vibrational patterns from the same two cheap, off-the-shelf devices to perform map tracing; and (4) a second user study showing both the feasibility and usability of the second prototype with blind and visually impaired users.

RELATED WORK
Giudice et al. [3] created a prototype to offer vibrational and auditory feedback to blind and visually impaired people that allowed the tracing of graphical information on a touchscreen. The vibration came from an Android tablet: as the users put their finger on the edges of a graphical item, such as a bar graph, the tablet would vibrate to let them know they were on a line. If users got lost or was uncertain what direction to turn, they could receive auditory feedback to indicate their last location in the graphical item. User studies showed this method to be effective and usable on graphical items such as letters and bar graphs. However, the drawback of this method is that auditory feedback may not always be desirable while in public places where privacy concerns or loud noises could be present. In two of their experiments, solid vibrations were used to designate lines and pulsating vibrations were used to designate vertices. However, the vibrational feedback did not inform the user in which direction the line was currently going. This research was continued with panning and zooming operations on maps [8] with good results.

In SpaceSense, users could listen to and feel directions with 9 vibrating motors [14]. The vibrating motors were attached to the back of the device, and they provided haptic information to give all 8 compass directions. For example, when directions said go to the west, the left side of the smartphone vibrated. Blind and visually impaired users were able to get a good sense of the map using this system. However, the use of 9 vibrating motors is expensive, drains the battery quickly, and is less likely to be implemented commercially.

TouchOver map allowed users to trace roads that vibrate on a smartphone [9]. When the user's finger moved off the road, the vibration would stop. Text to speech (TTS) information also provided the name of the street. Blind-folded sighted users were able to trace the maps, however, the user study was not done with blind and visually impaired individuals.

Kaklanis et al. explored the use of stereo sound and vibrations on a touchscreen to learn maps [4]. When the user touched the road, the tablet vibrated and stereo sound designated cross-roads. No user study was done.

Touchplates used plastic cutouts to help blind and visually impaired individuals save locations on a touchscreen map [6]. They could save a location with a specific cutout, such as a star, and place that cutout on the touchscreen. This would allow users to return to the saved location at any time. Users showed favorable responses to this type of map exploration.

Brock et al. [1] showed the feasibility of using tactile overlays on a touchscreen with motion detection by cameras. The on-camera motion detection helped to ferret out accidental touches such as palm touches. Their studies showed that limiting accidental touches was beneficial to the users.

Sucu et al. used two devices that vibrated at different times to allow users who are blind and visually impaired to steer a car without assistance [12]. They simulated driving with a game steerring wheel with two Nintendo WII controllers on each side. When the car was moving too far to the left, the left device would vibrate, and when the car was moving too far to the right, the right device would vibrate. Their results showed the feasability of this system.

Timbremap was a research project for blind and visually impaired individuals to learn maps on touchscreens through data sonification [11]. If a user's finger moved off the line, stereo sound was played to notify him or her which direction to go in order to get back on the line. User studies showed that this was a feasible system for blind and visually impaired people to learn maps.

Access overlays was a system to help users who are blind and visually impaired to learn maps on large touchscreens through three different techniques: edge projection, touch and speak, and neighborhood browsing [5]. Edge projection would place all the items on the edge of the screen, and the user could touch the edge to find the item such as a store they were looking for. Then, they could move their finger until they reached the location of the item on the screen. Touch and speak would allow the user to give voice commands to the system, and neighborhood browsing would provide the direction to the location they were looking for and its distance in inches. User studies showed these techniques were effective in allowing the users to learn the maps.

PROTOTYPE ONE

Our first prototype was designed to measure the ability of users who are blind and visually impaired to determine distance between two lines on a touchscreen using vibrational cues. An Android smart watch (Galaxy Gear Live) and an Android tablet (Nexus 10) were used to provide directional vibrational cues. Android was chosen over iOS because iOS tablets do not have haptic feedback. Besides the use of the tablet to provide directional vibrational cues, the touchscreen tablet was also used as the screen where the lines were traced.

In order to designate different distances, the vibrations pulsated at different speeds. Slower pulsations were used to designate further distances, and faster pulsations were used to designate shorter distances. The duration of the pulsations was a function of the distance from the finger to the end of the line in pixels of the touchscreen, defined in milliseconds as $t = distance \times 0.01$. For example, if the distance from the user's finger to the end of the line was 1000 pixels, then the vibration would pulse for 10 milliseconds on and 10 milliseconds off. Pulsating vibration was simulated in the software by sending signals at exact times to turn the vibrator off and on. The maximum pulsation duration was 15 ms given the longest line was 1500 pixels. The minimum vibration pulsation duration was 1 millisecond. The user would start with their finger in the bottom left corner of the screen, and the pulsations would be slower for the longer line and faster for the shorter line. The pulsation rate became the same between the short and long lines when the user's finger reached the end of the lines. The width of the lines was 8.99 mm, which has been shown to be the optimal width for line tracing according to psychophysical studies [10]. It was also used in the studies by Giudice et al. [3].

Three types of lines were traced: vertical (along the left vertical edge of the tablet), horizontal (along the bottom edge of the tablet), and diagonal (along a 45 degree angle). The lines were not graphically rendered for this prototype. All lines started in the bottom left corner, and paper guidelines were taped on the bottom and left edge of the screen to guide the user's finger along the line. When the diagonal line was traced, the paper guideline was placed at a 45 degree angle from the bottom left of the tablet to the top right (northeast, see Figure 1). The guidelines were necessary as the bottom part of the tablet contains software buttons such as back and home, which could be accidentally pressed. This test was not looking at the ability of the blind subjects to trace lines in a straight manner but was testing their ability to judge distances.

The smart watch was placed on the user's non-dominant hand. Users used one finger of their dominant hand to touch the tablet screen. The tablet was taped down to a desk to prevent it from moving during the test. The bottom edge of the tablet was lined up with the edge of the desk, and the desk was raised up or down for the comfort of each user. Realizing that taping the tablet down to the desk is not an ideal setting, in future work we will explore the use of the system by allowing the

Figure 1. Setup for User Study One showing the smart watch and the tablet with paper guidelines attached.

users to hold the tablet in their hands or set it on their lap. The first author of this paper, who is blind, used the system frequently during development and typically held the tablet in hand and had no difficulty using the system. While this is only anecdotal evidence, we believe it will not be difficult for other blind users to use the system in hand.

The tablet vibrated for the vertical lines. The watch vibrated for the horizontal lines. Both watch and tablet vibrated for the diagonal line. Note that for prototype one, we did not test the alternative combination with the tablet vibrating for horizontal and watch for vertical. The alternative combination of vibrational patterns was tested for Prototype Two (see User Study Two section).

USER STUDY ONE

Participants

A total of 6 visually impaired and blind users (3 males, 43 $\pm$ 8.63 years old), and 6 sighted users (2 males, 47 $\pm$ 18.7 years old) participated in this user study. The demographic data for blind and visually impaired users along with their causes of blindness are summarized in Table 1. Both sighted and blind participants with residual vision were blindfolded for this study.

Procedure

Participants were asked to compare two lines of different length and determine which of the two lines is longer. The participants were notified by a sound when they reached the end of the line. Once both lines had been traced, text to speech asked users for a response. Responses were recorded by swiping left if the first line was longer and swiping right if the second line was longer. The answering mechanism was made very insensitive to avoid accidental responses. The users were required to slowly move their finger left or right for a good distance to indicate which line was longer. To minimize potential overlap, they were asked to answer on a different section of the tablet than where they traced the two lines.

Part.	Sex	Age	Age onset	Cause	Residual Vision
P1	M	56	42	Uveitis, glaucoma	no
P2	M	35	1	Scarlet fever	Few shapes, colors
P3	F	35	21	Macular degeneration retinitis pigmentosa	Some peripheal vision
P4	F	46	12	Retinitis pigmentosa	some peripheal vision
P5	F	40	21	Retinitis pigmentosa	light perception
P6	M	34	Birth	Retinitis pigmentosa	No

Table 1. Participant Demographics for Study 1

Three conditions were tested: vertical lines, horizontal lines, and diagonal lines. Each condition had a block of 50 trials. For each condition, participants were given 5 trials to learn the system before the start of the test. The order of the three conditions were counterbalanced across participants.

A staircase method [2] (3 down 1 up) was used to determine the distance threshold. A static short line of 2 inches was used during all trials. The second line started out at 5 inches. The order of the two lines was randomly assigned for each trial. If the user answered correctly three times in a row, the longer line would have its length decreased by half the distance between the long line and the short line. For example, if they got the first three trials correct, then the distance between the lines would be reduced from 3 inches to 1.5 inches. If they got the next three correct, then it would be further reduced to .75 inches and so forth.

Results

We measured the blind and sighted participants' ability to determine the distance between two lines using a staircase procedure (3 down 1 up; 50 trials per condition). Thresholds were calculated by fitting the data with Weibull psychometric function and targeting 79.4% level on the psychometric function. These thresholds correspond to the distance in inches at which the participants can correctly detect the presence of length difference between two lines on 79.4% of the trials. As shown in Figure 2, distance thresholds were reported for all three conditions.

Two-way ANOVA comparing the effects of subject group and condition found a significant effect of group ($F(1, 32) = 4.85$, $p < 0.05$), with no significant effect of condition ($F(2, 32) = 2.27$, ns). As predicted, the overall threshold across all 3 conditions was significantly lower in blind than in sighted group ($t(34) = 2.27$, $p < 0.02$, one tailed). The lower distance thresholds in blind individuals suggest their enhanced ability to form representations of spatial distance from tactile vibrational cues.

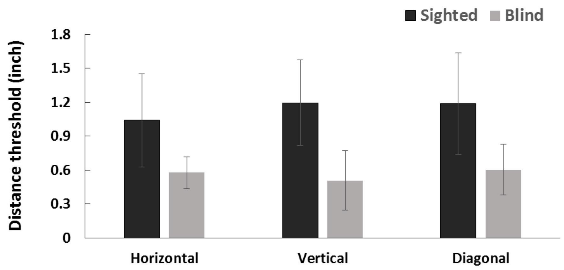

Figure 2. The distance thresholds for blind and sighted subjects for all three conditions: vertical lines, horizontal lines, and diagonal lines.

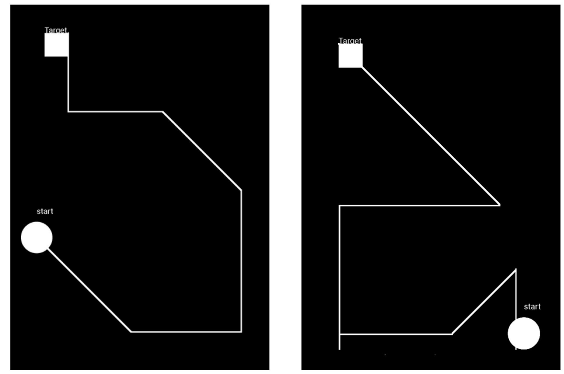

Figure 3. Two test maps used in User Study Two: test maps were made to have similar complexity. They were around 15-18 inches long, with 5 to 6 segments and 1 to 2 diagonal lines. The starting and ending locations were indicated by white circles and white squares, respectively.

PROTOTYPE TWO

In this study, we attempted to further explore the following three questions: (1) Is it feasible for people who are blind to follow map directions based on vibrational cues alone on a touchscreen; (2) Can people who are blind understand and utilize complex vibrational patterns in a practical application; and (3) Whether blind individuals have a preference for certain vibrational patterns.

Similar to the first prototype, our second prototype also consisted of an Android smart watch and an android tablet. It was designed to test a practical application in which the users trace maps using vibrational cues from two vibrating devices. A real-world application we envisioned for our system would be blind users tracing Google Maps on their smart devices using haptic cues as they walk down the street to find their destination.

We manually constructed 6 training and 6 test maps in Java on the Android tablet. The six training maps were made easy to familiarize participants with vibrational patterns. They were 5-10 inches long, with 3-4 short segments including one diagonal line. The six test maps were made to have higher complexity than the training maps. They were 15-18 inches long, with 5 to 6 segments including 1 to 2 diagonal lines (see Figure 3 for two test map examples). Due to the limited amount of space on the Nexus 10 touchscreen, test maps could not be made with the exact same complexity. All maps were constructed from vertical lines, horizontal lines, and diagonal lines. Note that lines were graphically rendered on the screen for Prototype Two. Similar to the first prototype, the line width was 8.99 mm and all diagonal lines were rendered at exactly 45 degree angles. Unlike the first prototype in which the diagonal line only went to the northeast direction, the second prototype used diagonal lines going in all four directions (i.e., northeast, southeast, southwest, and northwest).

We tested two conditions. Condition 1 involved the tablet vibrating for vertical lines and the watch vibrating for horizontal lines, whereas Condition 2 involved the tablet vibrating for horizontal lines and the watch vibrating for vertical lines. Note that for Prototype 2, the duration of the pulsataion was kept constant (300ms on and 300ms off). We used different vibrational patterns to distinguish between lines going north and lines going south, with lines going north vibrating solid and lines going south pulsating. Similarly, different vibrational patterns were used to distinguish between lines going east and lines going west, with lines going east vibrating solid and lines going west pulsating.

The vibrational patterns of horizontal and vertical lines were combined to create vibrational patterns for diagonal lines. For example, diagonal lines going northeast would have both tablet and watch vibrating solid at the same time, regardless of conditions. The lines going northwest would have the tablet vibrating solid and the watch pulsating (Condition 1), or vice versa (condition 2).

Map starting and ending locations were determined and placed visually on the screen. To increase the difficulty of the test, the starting and ending locations were made different for each map. One of the researchers (second author on the paper as the first author is totally blind) would guide the user's finger to the starting location. Timing was started once the user's finger touched the starting location. When the user reached the ending location, the timing was stopped and recorded in a log file. TTS would then provide the name of the next map (e.g., map 2 would be announced once they finished map 1). In order to prevent accidental starting of the recording, a 3 second delay was put in between two test maps.

The setup of Prototype Two was identical to that of prototype One. As shown in Figure 4, the smart watch was placed on the user's non-dominant hand. Users used one finger of their dominant hand to trace the map on the tablet screen. The tablet was taped onto a desk to prevent it from moving during the test. The desk can be raised up or down for the comfort of each user. As we acknowledged in User Study One, taping the tablet down to the desk is not an ideal setting, and in future work we will explore alternative settings.

USER STUDY TWO

Participants

6 visually impaired and blind users (5 males, 41.8 $\pm$ 12.5 years old) participated in this study. The first two participants (P1 and P2) also participated in the first user study. The

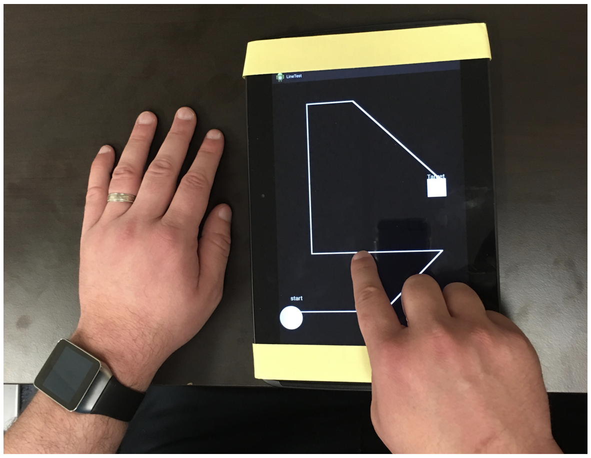

Figure 4. Setup for User Study Two showing a real user tracing one of the test maps based on vibrational cues from both the tablet and the smart watch.

Part.	Sex	Age	Age onset	Cause	Residual Vision
P1	M	56	42	Uveitis, glaucoma	No
P2	M	35	16	Scarlet fever	Few shapes, colors
P3	M	58	36	Cone rod dystrophy	Light perception
P4	M	41	28	Bechets syndrome	No
P5	F	33	Birth	Leber Congenital Amaurosi	No
P6	M	28	Birth	Microopthalmia	No

Table 2. Participant Demographics for Study 2

demographic data for blind and visually impaired users and their causes of blindness are summarized in Table 2. Blind participants with residual vision were blindfolded for this study.

Procedure

The participants were told how the prototype works and were then given 6 easy training maps to practice. If they could not remember the meaning of the vibrational patterns during practice, they could ask the researchers for instructions (see Prototype Two Section above for explanation of vibrational patterns). Training maps were not timed. Then, the participants were given 6 difficult test maps to complete. The two testing conditions were counterbalanced: half the participants were given Condition 1 first (tablet vibrating for vertical and watch for horizontal lines) and the other half of the participants were given Condition 2 first (watch vibrating for vertical and tablet for horizontal lines).

Testing maps were timed. During testing, instructions were given again if participants had difficulty remembering vibration patterns.

After the testing maps were completed, participants were asked about their preference for testing condition. They were also asked to rate three statements on a 5 point Likert scale where:

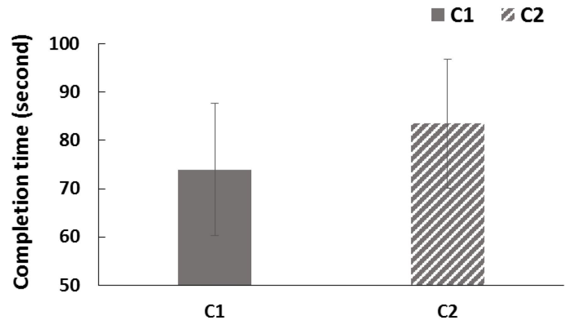

Figure 5. Average map completion time in second for Condition 1 (C1: tablet vibrating for vertical and watch for horizontal lines) and 2 (C2: watch vibrating for vertical and tablet for horizontal lines).

1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, and 5 = strongly agree. The three statements were: “I did not like the tablet vibrating for vertical and watch for horizontal”, “I did not like the watch vibrating for vertical and tablet for horizontal”, and “It was difficult to switch between the two conditions”. The statements were asked in the negative to avoid positive leading bias that tends to exist in research on assistive technology [13]. Then, the participants were asked if they had additional feedback regarding the prototype.

Results

Here we further explored the following three questions: (1) Is it feasible for people who are blind to follow map directions based on vibrational cues alone on a touchscreen; (2) Can people who are blind understand and utilize complex vibrational patterns in a practical application; and (3) Whether blind individuals have a preference for certain vibrational patterns.

We found that it was feasible for users to trace maps on a touchscreen using vibrational cues. All users were able to complete 12 testing maps (6 per condition) in a timely manner. As shown in Figure 5, it took blind users an average of 74 seconds to complete a map in Condition 1 (tablet vibrating for vertical and watch for horizontal lines), and 83 seconds to complete a map in Condition 2 (watch vibrating for vertical and tablet for horizontal lines). There was no significant difference in map completion time between the two testing conditions ($t(5) = -0.53$, ns, 2 tailed).

All users were able to understand and utilize complex vibrational patterns. It was easy for them to learn the vibrational patterns for horizontal and vertical lines. Only a few times did a few participants have trouble recalling vibrational patterns for certain diagonal lines. For a real-world application, a good built-in tutorial and the functionality allowing users to relearn complex vibrational patterns would be beneficial.

As a group, blind and visually impaired users showed no overall preference for testing condition. The Likert scales for the first two statements were not statistically different ($t(5) = -1.46$, ns, 2 tailed). Furthermore, participants had no trouble learning different vibrational patterns and switching from one testing condition to another. This was supported by their Likert scales for statement three (2.3 with standard deviation

1.4). Interestingly, two participants did report a preference for Condition 1 (tablet vibrating for vertical and watch for horizontal lines).

After the test the participants were given the opportunity to provide feedback on the prototype. Overall, participants enjoyed using the prototype. One participant said the prototype was ’challenging, fun, and interesting’, and it reminded him of a video game he had played in the past. They thought the prototype was ’very cool’, ’really good’, and ’has potential for a lot of practical applications’. They believed that this prototype would be especially useful in a noisy environment (e.g., on a busy street or bus) where you can rely on vibrational rather than auditory cues.

Participants also provided constructive criticism of the prototype. Two participants mentioned that it was easy for them to swerve off the lines, and it took a while for them to learn how to backtrack with their finger and find the line again. One participant thought that the lines were too thin. About half the participants commented that the watch vibration on the wrist was relatively weaker than the tablet vibration on the finger. It was therefore harder for them to sense the vibration from the watch when both devices were vibrating. One participant suggested the prototype should have the ability for TTS to indicate how far the end of the line is in scaled miles or yards. These comments would allow us to improve our prototype for real-world applications.

Discussion and Comparison

Compared to Spacesense [14] in which users took on average 201 seconds to learn map instructions, the average map completion time of our system was shorter (74 seconds in C1 and 83 seconds in C2). This is despite the fact that test maps in our system had more streets and turns than maps in Spacesense. However, in Spacesense users were allowed to explore the map more than once until they felt they had learned the route. Also Spacesense provided information through audio and tactile cues based on Google map directions but did not allow users to trace the maps with their finger.

In Timbremap [11], the users were given as much time as they needed to explore and learn the maps through sonification. One participant took 14 minutes to learn a map and 10 minutes to learn another. They used more complex maps than ours and were aimed at examining users’ ability to understand maps as a whole rather than their abilities to follow specific directions. Similarly, TouchOver Map allowed the users 15 minutes to explore and learn a map [9]. Giudice et al. [3] tested users’ accuracy of identifying shapes after spending a certain amount of time learning them, but they did not report average learning time.

It has been shown in previous studies that learning through touchscreen with audio and tactile feedback of maps is feasible and effective. Our study mainly looked at how blind users can perform map tracing on touchscreens based on vibrational cues alone. While it is hard to directly compare our results to those from previous studies, our system did show promising map completion time.

FUTURE WORK

We did not compare sighted against blind and visually impaired individuals in our second user study. Given that blind and visually impaired users were better at determining distances between vibrational lines (User Study One), it is likely that they would be faster than sighted users to complete map tracing on a touchscreen through vibrational cues. This prediction can be tested in future user studies.

When using tactile maps, blind and visually impaired users might prefer to get street and landmark information such as street names and nearby grocery stores through TTS. Adding this information would allow us to test our prototype with real maps. It would be interesting to examine users’ ability to follow both vibrational and auditory feedback. For example, how much speech information could they process while attending to the vibrational cues, and what is the optimal speed for speech to be effective.

While at group level there was no statistical difference between two testing conditions in User Study Two, two users reported a preference for condition one (tablet vibrating for vertical and watch for horizontal). A user study with more blind participants would allow us to further test this potential preference.

Lastly, participants sometimes would swerve off the lines and had to trace their finger back to the line. In future work, we could alert them by reducing the intensity of the vibration instead of simply stopping the vibration. We could test whether such information is beneficial in facilitating the completion of map tracing.

CONCLUSION

We designed two prototypes that both consisted of an Android watch and an Android tablet. The first prototype was aimed at testing the ability of users with visual impairments and blindness to determine distance between two lines on a touchscreen based on vibrational cues from two devices. We showed that blind and visually impaired individuals had lower distance thresholds than sighted users across three line conditions (i.e., vertical, diagonal, and horizontal). This suggests that compared to sighted users, blind and visually impaired users are better at representing spatial distance based on vibrational cues.

The second prototype was designed to test blind users’ ability to trace maps on touchscreens using complex vibrational patterns. We showed that blind and visually impaired individuals were able to trace the maps in a timely manner and enjoyed learning and utilizing complex vibrational patterns for directions. These results suggest not only the feasibility but also the usability of our prototypes. Additional features, such as auditory feedback, can be incorporated into the current prototype. The effectiveness of adding additional information will be tested with real-world maps in future user studies.

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