LineChaser: A Smartphone-Based Navigation System for Blind People to Stand in Lines

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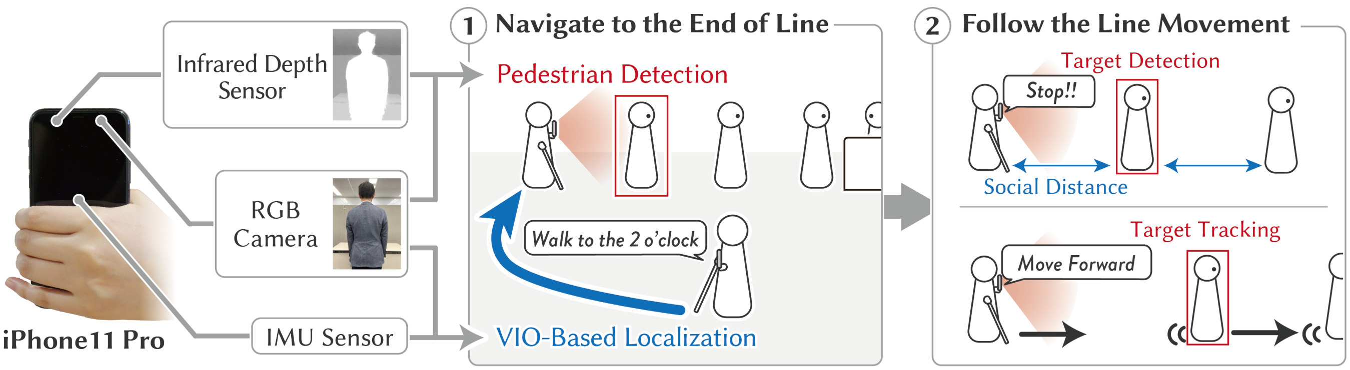

Figure 1: LineChaser helps blind people stand in waiting lines in public spaces by using only off-the-shelf smartphones. The system guides the blind user to the end of the line, and then helps them follow the line movement.

ABSTRACT

Standing in line is one of the most common social behaviors in public spaces but can be challenging for blind people. We propose an assistive system named LineChaser, which navigates a blind user to the end of a line and continuously reports the distance and direction to the last person in the line so that they can be followed. LineChaser uses the RGB camera in a smartphone to detect nearby pedestrians, and the built-in infrared depth sensor to estimate their position. Via pedestrian position estimations, LineChaser determines whether nearby pedestrians are standing in line, and uses audio and vibration signals to notify the user when they should start/stop moving forward. In this way, users can stay correctly positioned while maintaining social distance. We have conducted a usability study with 12 blind participants. LineChaser allowed blind participants to successfully navigate lines, significantly increasing their confidence in standing in lines.

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CCS CONCEPTS

• **Human-centered computing → Accessibility technologies**; • **Social and professional topics → People with disabilities**.

KEYWORDS

visual impairment, orientation and mobility, pedestrian detection, line detection

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1 INTRODUCTION

People often need to stand in waiting lines in public spaces in daily life, such as at cashier stations, bus stops, and check-in-counters at airports. This activity is challenging for blind people due to their lack of vision. People are first required to find the end of a line, a position that dynamically changes over time. It is difficult for blind people to find the end of line using information gathered by their senses (*e.g.* auditory cues) or tools (*e.g.* canes), and thus depend on the assistance of nearby people. Recent research has proposed high-accuracy indoor navigation systems to help blind people reach a destination based on static topological route maps and localization techniques [7, 11, 12, 15, 18, 25, 33, 34, 40, 41, 44, 48, 52, 57]. These systems can help users reach the *fixed* entrance of a waiting line area, but they did not focus on navigating to a changing end-of-line position.

Once a person joins a line, the next step is to follow the person in front of them as they move intermittently. Lines in public spaces are not always straight, as is the case, for example, in the long serpentine lines at airports. It is challenging for blind people to maintain a consistent distance from the person ahead of them only with their senses and tools. The larger distance currently required to comply with social distancing during the COVID-19 pandemic has increased this challenge [20]. Recent research has aimed to help blind people avoid collisions with pedestrians [25, 28]. These systems can detect positions and movements of nearby pedestrians by using computer vision technologies, but they have not been applied to line navigation.

We first developed a prototype system by focusing on the task of tracking and following a line, and recruited six blind people to test the system as a preliminary user study. The prototype system is capable of detecting and reporting the distance to the person in front of the blind user continuously using only a smartphone with an RGB camera and an infrared depth sensor. The sensing results are used to alert the users with three levels of distance information via vibration patterns to allow users to start moving forward and stop in a synchronized manner with the other people. All participants commented that they have had previous experiences where they did not sense that the line was moving or, conversely, did not notice the line had stopped and bumped into the person in front of them. The prototype system enabled blind participants to detect the movement of the line and thus stand in lines with increased confidence. However, we observed several situations where the participants followed a wrong person who happened to be standing in front of the *target* (the correct person to follow).

We used feedback on the prototype system to design a smartphone-based assistive system called *LineChaser* (Figure 1). The system enables a blind user not only to follow line movements but also to find the end of a line. The system uses a topological route map that contains the line information, such as the place where pedestrians usually form a line. LineChaser first guides the blind user to the end of a line by using the map and a localization method with the smartphone (Figure 1, action (1)). To navigate, the system uses the smartphone's built-in RGB camera and infrared depth sensor, respectively, to detect nearby pedestrians and estimate their 2D positions on the map. According to the position estimation, LineChaser determines whether pedestrians are standing in a line. After guiding the user to the end of the line, LineChaser detects the last person in line (we call this person the target), and tracks the target based on the color histograms and positions of detected pedestrians (Figure 1, action (2)). LineChaser then uses the sensing results to instruct blind users to advance to the front of the line by moving in the right direction at the right time. We also take account of "social distancing," the distance to be maintained from other people to prevent possible infection with COVID-19. Our interview revealed that many blind people cannot maintain social distancing, as complying to it impedes blind people from having the target from aural sensing area, making it difficult to follow the target. Therefore, the system is also designed to maintain proper social distancing from the target.

To understand the usability of our system, we conducted a second study with 12 blind people. In this study, we prepared two types of lines (straight and serpentine) and asked blind participants to find the end of the line and follow the line movement with LineChaser. The results show that all participants were successfully able to both find and follow lines while maintaining social distancing. Our questionnaire results suggest that blind people face everyday difficulties when standing in lines. Also, blind participants significantly increased their confidence in standing in lines after using LineChaser, comparing to their daily experience. We also discuss future requirements to further improve LineChaser and possibly integrate it with other systems that provide day-to-day assistance for blind people.

2 RELATED WORK

2.1 Navigation System

Existing commercial navigation systems (*e.g.* Google Maps [23], Ariadne [13], SoundScape [38] and BlindSquare [39]) and researches provide turn-by-turn instructions with localization methods using global positioning system (GPS) [7], magnetic information [22, 48], visual features [34, 57], radio frequency identifier (RFID) tags [12, 15, 18, 44], visible light communication (VLC) [41] and bluetooth low energy (BLE) beacons [11, 32, 40, 52]. They use static topological route maps to navigate users to front of a destination with acceptable accuracy (*e.g.* 1.7m average [40]). It means that they were not designed to navigate users to a dynamically changing end-of-line position. We aim to propose a system to complement existing navigation systems to support line standing tasks.

2.2 Smartphone-based Assistance System

Sighted assistance system such as Aira [4] and BeMyEyes [6] can be considered as one solution. While it is possible to use such services for the line standing task, it is also helpful to offer non-manual solutions to improve their independence. These services require human labor for assistance and thus may not be scalable when many users require assistance, may have limitation for service cost reduction, and may not be easy to provide round clock service for worldwide clients.

Computer vision-based systems have become popular among blind people. Seeing-AI [37], Or-Cam [43], TapTapSee [14], Aipoly [3] and Envision [10] are examples of such. These systems are able to recognize and read printed letters and even provide simple captions to pictures taken by the blind user, but they are not designed to detect surrounding people with sufficient accuracy for blind people to follow a line. It is necessary to detect the positions of surrounding pedestrians and convey suitable distance and direction information to enable line standing tasks. Accordingly, our system adopts the depth sensor of an iPhone 11 Pro and object detection system to obtain the positions of surrounding pedestrians.

2.3 Obstacle Avoidance System

Researchers have developed supportive technologies that allow blind users to avoid potential obstacles(*e.g.* walls [27, 53], boxes [26, 27, 46], chairs [34, 53], poles [46, 50]) by detecting them using various sensors and lasers. Some pedestrian avoidance systems acquire positions of surrounding pedestrians to generate a pedestrian-avoiding route for safe navigation [25, 30]. Also, the iPhone operating system (iOS) 14.2 with the built-in LiDAR sensor supports detecting and measuring the distance with people nearby. However, it is insufficient just to acquire the positions of surrounding pedestrians to stand in lines. It is also necessary to determine whether the detected people are standing in a line. By doing so, it is possible to find the end of a line and follow the target. Thus, we implemented a system that distinguishes people standing in line from people who are not. We implemented this system by combining the results of an object detection system and a pre-determined map.

2.4 Robots that Stand in Line

Nakauchi *et al.* designed a robot that finds the end of a line and follows the person in front of it [42]. Given the starting point and rough shape of the line, the robot eventually finds the end of the line by scanning each person in the line from the front of the line until no person is detected. This algorithm is effective for a robot as it is capable of changing its' orientation frequently. However, frequent instructions to change their path and orientation might disorient blind people [30]. We therefore implemented a system to support the standing-in-line task with a single smartphone and investigated the suitability of the interface and navigation method for blind people by conducting a user study.

2.5 Navigation Interface for Blind People

Navigation systems for blind people commonly use an audio interface. Proposed audio interfaces can be categorized as follows: 1) text-to-speech [15, 26, 29, 34, 48, 52]: reads out information or expected route; 2) beep sounds [28, 30, 50]: uses beep sounds to convey there is a risk of collision; 3) sonifications [2, 16, 46, 57]: conveys information about distance or size by encoding them to acoustic parameters; 4) clock positions [7, 32, 35, 41, 51]: conveys distance and orientation of a destination using directions represented by clock; 5) 3-D sounds [38]: conveys information about distance and orientation by mapping them into stereophonic sound space.

Tactile interfaces are also used in navigation systems [19, 27, 29, 30, 36, 51, 53] and learning maps [21, 24, 45]. Previous researches reported that vibration feedback has the following advantages over auditory feedback: 1) blind users can receive tactile feedback while listening to ambient sounds [30]; and 2) audio might be less effective in noisy and crowded environments [8]. On the basis of these previous works, we adopted vibration feedback for the navigation interface in our preliminary study.

Based on the preliminary study, we implemented a navigation interface using both audio (clock position) and vibration feedback. We used audio feedback with the clock position to convey distance and direction and vibration as positive feedback when the blind user is facing the correct direction. Our interface was designed based on the study by Yoon *et al.* [57]. Their smartphone-based indoor navigation system conveyed the general direction using audio and used both vibration and audio feedback when the user was facing the destination. Additionally, an auditory interface that gives directions using the clock position has well been observed in past research [7, 32, 35, 41, 51]. It is capable of conveying distance and direction concisely to the blind user. We adopted clock position because it has been widely used in Japanese blind community [1] and also by previous navigation systems [7, 32, 41, 51]. On the basis of the preliminary study, we also adopted a method of providing audio feedback based on clock position.

3 PRELIMINARY STUDY

We conducted a preliminary study with six blind people to understand: (1) their daily experience and challenges while standing in line; and (2) how to design a smartphone-based system that helps blind people stand in line. We implemented a prototype system that helps blind users to sense line movement, and asked blind participants to use the system. This experiment was reported in the ACM CHI '20 LBW paper [31].

3.1 Prototype System

3.1.1 Pedestrian Detection and Distance Estimation. We used an off-the-shelf smartphone, iPhone 11 Pro[1], which is equipped with RGB image sensors and an infrared depth sensor. The system first detects pedestrians from the RGB streams by using a vision-based object recognition engine, YOLOv3-tiny [47], which recognizes "human" as an object type. Then, it automatically generates bounding boxes for all humans and selects the largest one as the target. The distance to the target is estimated from the depth data at the target's central position (Figure 2 (a)).

3.1.2 Vibration Alerts. To convey distance information, we relied on vibration alerts, as audio might be less effective in noisy, crowded environments [8]. The system emits three types of vibration alerts:

(1) **Signal to stop** indicates that another person is standing within 50 cm of the user and that the user should stop moving. We used a long vibration alert (pulse duration (PD) of 0.5 s and inter-pulse interval (IPI) of 0.25 s) (Figure 2 (b-1)).
(2) **Signal to move forward** indicates that a person is standing in front of the user at a distance greater than 50 cm. The signal is used to prompt the user to step forward and uses a two-pulse vibration. (Figure 2 (b-2)).
(3) **Obstacle signal** indicates an imminent risk of collision with any obstacle (pedestrian, desk, or wall) located less than 50 cm away. We used a short vibration alert (PD and IPI of 0.1 s) as the signal (Figure 2 (b-3)).

The absence of vibration indicates that the user has lost the target. In that case, users should scan the environment with their phone to find them. We set the alert distance threshold to 50 cm, because the distance of personal space while standing in line is around 40–80 cm [42] and users hold the smartphone in front of them.

[1] https://www.apple.com/iphone-11-pro/

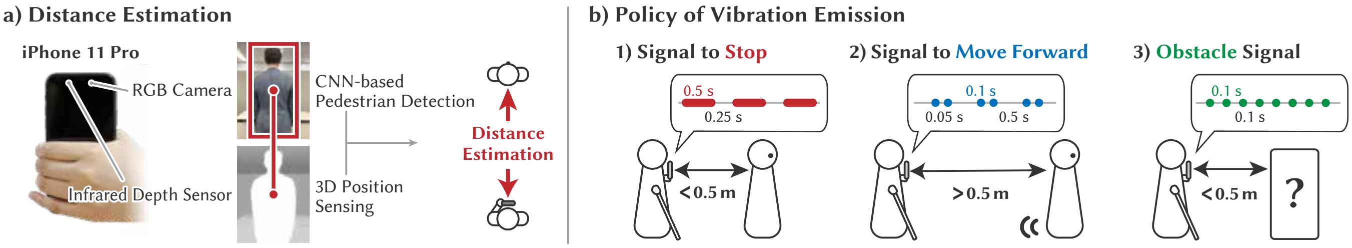

Figure 2: Overview of preliminary prototype system. a) The system uses an off-the-shelf smartphone to detect pedestrians and estimates the distance to them. b) The system emits three types of vibration alerts to provide position information to users.

3.2 User Study Setup

We recruited six blind participants (four male and two female), aged 22 to 33 years old (mean=26.17 and SD=5.34). All participants were completely blind and used a cane as their navigation aid.

3.2.1 Tasks and Conditions. All tasks started with five people in line. The blind participants were asked to follow a line formed by four sighted people (hereafter called *extras*) in front of them (Figure 3 (a)). They were asked to stand in line and proceed until reaching the reception desk (the goal). A researcher signaled for the extra standing in the front position to leave the line after 30, 60, or 90 s. Waiting times were randomized for each extra and trial. Each blind participant held a smartphone with one hand and used their cane with the other hand. We stopped the task if the participant overtook the target in front of them, also referred as extra 1 in Figure 3 (a). We designed two types of organized straight lines. In condition C1, four extras moved one by one. In condition C2, two randomly selected extras in consecutive positions – extras 1 to 4 in Figure 3 (a) left the line together (*i.e.* one extra left the line at the same time as the person in front of the extra left the line). Condition C2 was designed to evaluate the response to irregular line movement. To simulate a crowded public space, we played ambient noise recorded at a shopping mall at 60 dB [49].

3.2.2 Procedure and Metrics. We administered a pre-questionnaire in which we asked participants about their prior experiences and the challenges they faced when standing in lines. We also asked them to rate a set of statements (Q1–Q5 in Figure 4) using a 7-point Likert scale (from 1, strongly disagree, to 7, strongly agree). A training session lasting 10–15 min was then given to participants.

Then, the blind participants performed six trials (three C1 and three C2) where they stood in line using our system until reaching the reception desk. The order of the line conditions was randomized for each participant. To understand how the line moved, we defined seven positions around the target as the *stop positions* of a participant (Figure 3 (b)). Ideally, the participant stopped in the position immediately behind the target (Back in the figure), but a slight deviation to either side (Back Left or Back Right) was also acceptable. After the trials, participants were asked a set of questions to gauge their confidence and sense of comfort (Q1–Q5), to rate the system on a system usability scale (SUS) [9], and were also asked open-ended questions to gather qualitative feedback.

3.3 Results and Discussion

3.3.1 Past Experiences and Opinions about Standing in Line. Participants (P1–P6) reported standing in line in various situations, such as counters at stores and airports, at a bus stop, and getting on the subway. Most participants reported trying to cope with standing in lines by their intuition with ambient sounds (P1, P2, and P6), asking people in line for help (P3), or touching the clothes of the person in front (P5). P4 reported that he does not stand in line by himself.

Despite their various strategies for standing in line, all participants reported occasions during which they did not realize the line was moving or bumped into the person in front of them: A1: *"In noisy places such as shopping centers and stations, it is hard for me to recognize when the line was moving. Even if I noticed the line movement, I can't sense the distance to the person in front."*[2] (P6); and A2: *"Lines are not always straight. For example, when I stand in a serpentine line, it is difficult to determine the direction I should walk in."* (P1).

3.3.2 Overall Performance. Figure 3 (b) shows the distribution of positions where participants stopped after each line movement. While the maximum trials in the study are 126 trials, we stopped the experiment as there was an occasion where P2 in C2 stood in front of the target person. As a result, the actual total number of trials was 125. Overall, participants successfully stopped just immediately behind the target (86.4%, 108 out of 125). We also noted that each blind participant tended to shift to a specific side during each line movement. The success rate for stopping at the correct position was 94.4% (118 out of 125) after including slight deviations to the side. The task success rate for line conditions C1 and C2 was 75% (18 out of 24), because we stopped each trial after one failure. Specifically, participants P3 and P2 overtook the target two and four times, respectively. Figure 3 (c) shows an example of a failure case. When the user shifted to one side and lost the target, the user scanned the area to relocate the target (Figure 3 (c-1)). However, in this case, the system detected another person and the user miss-tracked the target. (Figure 3 (c-2)). As a result, the system prompted the user to move forward, even though the actual target was standing on the user's left.

3.3.3 Subjective Ratings. Figure 4 shows the post-questionnaire results, in which most participants reported feeling more confident and comfortable standing in line after the experiment (with the system) than before (without the system). For questions Q1–Q4, all participants except P3 for Q3 increased their scores after the

[2] All of the communications with participants were done in their native language. In this paper, we describe any translated content in the form of *"translated content"*.

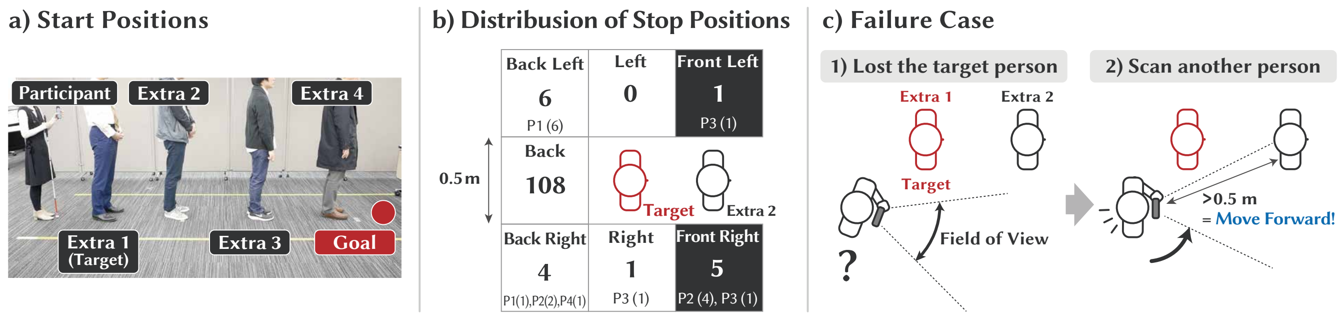

Figure 3: a) Starting positions of each line condition, b) Distribution of positions where blind participants stopped, and c) Example of a failure case where a participant overtook the target.

Figure 4: Likert scores and summary of responses before and after the preliminary experiment.

experiment. Four participants (P2–P5) also increased the score of Q5. The six SUS scores [5] given by the six participants were 77.5, 37.5, 80, 87.5, 97.5, and 90 (mean=78.3 and SD=21.3). Only participant P2 gave a lower score, mainly because they had difficulty in holding the smartphone.

3.3.4 Qualitative feedback. Participants generally agreed that the system allowed users to start and stop moving forward at the right time, as illustrated by their comments: A3: *"The biggest advantage of the system is that I could easily recognize the movement of a step forward from the person in front."* (P1); A4: *"By using the system, I could decide when and how far I should move forward."* (P4); and A5: *"The system provides information on the distance, so it can reduce risks of collisions."* (P2).

Some participants provided positive feedback on our smartphone-based interface: A6: *"The system is implemented on a smartphone. This is a strong advantage since it means I don't have to carry extra devices."*; and A7: *"The system was simple and easy to use."* (P4). In contrast, P2 commented that keeping the position of the system while waiting in line was difficult due to the large and heavy system: A8: *"This smartphone is big and heavy, so it was difficult for me to hold the smartphone stably."* (P2).

When asked for suggestions, two users mentioned that the system should provide more detailed distance information or the directional information of the target: A9: *"When I lost track of the target, I had to relocate the target by myself while changing the direction of the system. I want to know in which direction the target is standing beforehand."* (P4); and A10: *"I like to know more detailed distance information. It could be a good feature to be able to change the pulse duration continuously to encode distance information."* (P1).

3.4 Findings

We summarize our findings as follows: 1) Blind people face difficulties when standing in line to accomplish daily living tasks at subways, stores, cafes, and other public places, even when they use a cane and auditory senses. 2) Our prototype system allowed blind participants to follow the line movement successfully with increased confidence. 3) More detailed information on the distance or direction might further improve the efficacy of the system. 4) The cause of all task failures was incorrect positioning, due to miss-tracking of the target. On the basis of these findings, we designed and implemented LineChaser.

4 IMPLEMENTATION

This section describes the implementation of LineChaser. As shown in Figure 5, LineChaser uses a floor map that includes the line information to guide the user to the end of the line. Then, the system detects and tracks the target to follow their movement.

4.1 Map Preparation and Localization Phase

To localize the user's current position, LineChaser uses a floor map prepared in advance and ARKit to detect augmented reality (AR) markers placed on walls. We note that there is prior work on

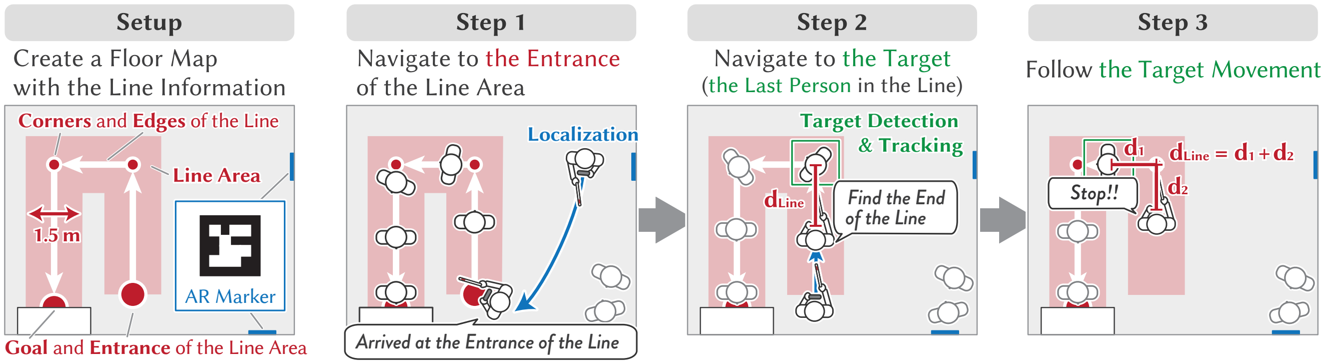

Figure 5: Overview of the navigation strategy. LineChaser uses a floor map that includes the line information, such as the line area, the entrance of the line area, and the corners of the line. (1) The system localizes the user's position via ARKit and AR markers placed on the wall, and guides the user to the entrance of the waiting line area. (2) Then, it guides the user to the target, the last person in the line. (3) The system tracks the target to follow the movement of the line.

smartphone-based indoor localization [32, 40, 44, 52], and the aim of the present work is not to advance the state-of-the-art in this respect. Instead, our contribution is the analysis and development of practical assistance for blind people to stand in lines based on such localization results.

4.1.1 Map Preparation. A map that consists of the information of where a line might form is created (Setup in Figure 5). First, we place an initial AR marker on the floor and scan it with the front RGB camera of the smartphone. Subsequently, we add the locations of the entrance, corner and line destination in the map. The orientation of the line is recognized by the directed edges of the line. Edges made by connecting each placed corner represents the center of the line. The width of the line is determined as a distance from both sides of the center of the line. Simultaneously, we place and scan additional AR markers to help users re-localize their position while they are standing in line. Finally, LineChaser creates a map that records all positions of the line relative to the AR markers.

4.1.2 Localization. While performing the task of standing in line, LineChaser localizes the user's current position and orientation on the prepared floor map. After the map is prepared, the blind user can now scan the initial AR marker to load the prepared map and localize their position on it. The system keeps track of the user's position using visual inertial odometry [57], which is supported by ARKit[3], whose localization errors generally range from 0.27m to 0.74 m [57] in a route about 61m long. The system tracks the user's position by combining the smartphone's motion tracking sensors and computer vision-based analysis of notable features obtained from the built-in rear RGB camera of the smartphone.

4.2 Line-standing Phase

4.2.1 Finding the End of the Line. LineChaser first guides the user to the entrance of the line and then locates the end of the line. The system conveys the direction and distance toward the entrance of the line (Figure 5, (Step1)). Upon reaching the entrance of the line, the system instructs the user to walk along the line area (Figure 5 (Step2)). While walking along the line area, the system detects nearby persons to search for the person standing at the end of the line (the person detection algorithm is described in section 4.2.2). When the system detects the person who is the last person in the line, the system recognizes this person as the target. At this point, the system acquires the initial color histogram of the target (Section 4.2.2). Finally, the system assumes that the blind user has now been guided to the end of the line and begins the line following task.

LineChaser navigates the user along a simple straight line connecting the user's current position with the entrance of the line. We note the existence of prior work on path planning for autonomous robots [17] and blind navigation [25]. These systems can generate a safe path that avoids obstacles, such as walls and static structures, using information from a LiDAR sensor to represent the structural surroundings. This study focused on developing a navigation interface, rather than a new path planning system.

4.2.2 Person Detection and Target Tracking with Color Histograms. LineChaser uses the front camera of the iPhone 11 Pro and YOLOv3-tiny [47] to detect pedestrians in the same way as our initial prototype system (Figure 2 (a)). Based on the calculated bounding boxes and the depth data from the iPhone, the system estimates the positions of detected pedestrians in the map coordinate system.

The failure case during the preliminary study occurred because of miss-tracking of the target (Section 3.3.2). Therefore, we implemented a new target tracking system. LineChaser first tracks each person based on the calculated positions for each frame (See [28] for the concrete algorithm[4]). We observed that the system can track persons at a rate of around 15 frames per second.

LineChaser uses the results of person tracking to track the target. The system distinguishes tracked people by the color of their clothes, which corresponds to the color histogram of the center area of their bounding box. When the target is initially recognized (Section 4.2.1), the system acquires his or her color histogram. Out

[3]https://developer.apple.com/arkit

[4]Based on our observations, we set the parameter values of the algorithm $\alpha = 0.5$ m and $\beta = 15$ frames for all of our studies.

of all detected persons, the system selects the person with the minimum value of histogram distance between the color histogram of the target and that of the detected person. For histogram distance, we adopted the Bhattacharyya distance for each a and b dimension in the Lab color space. If the histogram distance is below the threshold γ, the system recognizes the person as the target. We set the parameter value $\gamma = 0.40$, which is 40% of the maximum value of the color histogram distance.

4.2.3 Following the Target. After finding the person at the end of the line, LineChaser then instructs the user to follow the target. The system calculates d_{Line}, the distance between the user and the target along the waiting line, as shown in Figure 5, (Steps 2 and 3). The system instructs the user to maintain a distance of $d_0 m$ from the target. When $d_{Line} > d_0$, the system prompts the user to move forward. When $d_{Line} \leq d_0$, the system instructs the user to stop (Figure 5 (Step3)). We set the parameter value $d_0 = 1.7$ m, to maintain social distancing.

4.2.4 Considering Social Distancing. As reported in section 3.3.1, blind people usually either listen to ambient sounds or rely on others to navigate a waiting line. Since the outbreak of COVID-19, blind people, like everyone else, need to maintain a protective social distance between themselves and others. This prevents them from relying on the methods reported in section 3.3.1 to navigate the line. Therefore, we have adjusted LineChaser to maintain the social distancing.

4.3 Audio and Vibration Interface

LineChaser uses both audio and vibration interfaces. The audio interface conveys information about direction and distance, and the vibration interface prompts the blind user to move or stop when the user is facing the correct orientation. Participants in the preliminary study preferred to know detailed information about distance and direction to the target (A9 and A10). To take this user feedback into account, we used audio (text-to-speech) feedback for the main user interface. The audio interface can convey various types of information such as clock positions [7, 32, 35, 41, 51] or whether to move right or left [15, 16, 52, 57]. To convey a specific direction for navigation, we adopted a method based on clock position. Loomis *et al.* showed that instructions with clock position are capable of guiding blind people to a specific destination [35]. To explicitly convey the position of the destination to the user, for example, the system says *"Walk to the 2 o'clock, 2.1 meters ahead."* Any time the user shifts more than 30° from the expected orientation, the system repeats the instruction to the user to turn them toward the destination. In other words, the system is silent when the user is facing the expected orientation. Also, to keep the blind user in the center of the line when they are shifting aside, the system guides the blind user to slide left or right towards the center of the line.

An example of audio instructions during the line-standing phase is as follows: **1) Starting navigation:** *"Walk to the 2 o'clock, 2.1 meters ahead."*; **2) Arriving at the entrance of the line:** *"You arrived at the entrance of the line. You will now be walking along the line."*; **3) Finding the Target:** *"Target[5] found. Stop. The target is at the 1 o'clock, 1.5 meters ahead."*; **4) Following the line movement:** *"Walk to the 12 o'clock, 1.4 meters ahead towards the target."*; and **5) Ending navigation:** *"You are now in front of the line."*.

We also integrated vibration feedback for the additional user interface, as using a double encoding of the information with both audio and vibration feedback can increase the understandability of the feedback [21, 24, 56]. We used a weak, short vibration for move signal (Each set of move signal using three-pulse-vibration: PD of 0.1 s and IPI of 0.17 s. Interval between each move signal is 0.5 s). LineChaser vibrates weakly when the blind user is facing the correct orientation and indicates to move forward. This enables the blind user to correct their orientation because they only have to face the orientation which the system vibrates weakly. As long as the user can perceive this weak vibration, he or she can walk forward until the next instruction is enunciated. Blind users are instructed to stop when they cannot perceive this vibration. Even if the user is facing the correct orientation, but the distance to the target is within 1.7m, the system will stop vibrating, indicating that the user should stop. For the emergency stop signal, we use a long and strong vibration (PD of 0.4 s and IPI of 1.0 s). This vibration is used to alert the user that they are in imminent risk of collision. If there is an obstacle in the camera field of view within 0.50m, the system alerts the user with a long and strong emergency vibration. Upon sensing this vibration, the user is expected to stop and wait for the next audible instruction.

5 USER STUDY

To evaluate the effectiveness of LineChaser, we performed a user study with 12 blind participants. We recruited blind people who are able to use their cane or guide dog to independently travel and who often travel independently. Also, P2 in the preliminary study and P12 in the main study were the same person. Therefore, we will report our quantitative results without the results with P12 in Section 6.2 and Section 6.3 because she might have a learning effect due to the participation in both studies. As shown in Table 1, we recruited 12 blind participants (eight females, four males) aged 23 to 58 years old (mean=43.8 and SD=12.1). All participants considered themselves to have good orientation and mobility skills. Also, all participants used smartphone in their daily lives for more than three years.

5.1 Tasks and Conditions

The blind participants were asked to find and follow a line consisting of two to four extras in front of them (Figure 6). To prevent the spread of COVID-19, we asked extras to cover their face with a mask and a face shield, and maintain social distancing (1.5 m) while standing in line. Similar to the preliminary study (Section 3.2.1), blind participants were asked to proceed until reaching the reception desk (the goal). All of the blind participants except P10 held the smartphone in their left hand and cane in their right hand. P10 held the smartphone with the right hand and the guide dog in the left. Blind participants were first placed 5 m away from the line in an initial position and orientation that were both randomized in each trial. There were two starting positions (**S1** and **S2** in Figure 6) and three initial orientations (**O1**, **O2**, and **O3** in Figure 6). After the blind participant successfully found a line, a researcher signaled

[5] We used the phrase "target" because it was a concise way to express "the person in front."

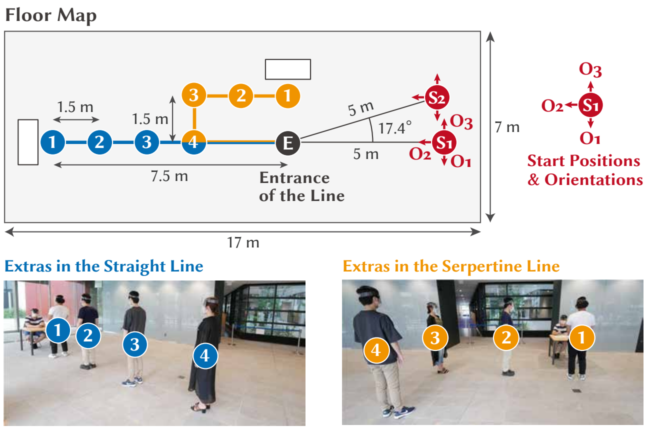

Figure 6: Overview of user study set up

ID	Age	Gender	Navigation Aid	SUS (Grade)	
P01	58	Female	Cane	60	D
P02	44	Female	Cane	77.5	B+
P03	56	Female	Cane	82.5	A
P04	53	Female	Cane	90	A+
P05	23	Male	Cane	82.5	A
P06	57	Female	Dog (primary) and Cane	90	A+
P07	49	Male	Cane	80	A-
P08	45	Female	Cane	90	A+
P09	38	Male	Cane	87.5	A+
P10	47	Female	Dog	82.5	A
P11	24	Female	Cane	100	A+
P12	33	Female	Cane	72.5	C+

Table 1: Participants' demographic information and their values for SUS scores.

the extra standing at the front of the line to leave the line randomly after 20, 40, or 60 s.

We designed two types of lines: **L1** was organised straight line and **L2** was organised serpentine line (Figure 6). Each blind participant completed six trials (three trials for each L1 and L2) of the standing-in-line task. We changed the number of extras (from two to four) in line for each trial to vary the position of the end of the line. When L2 trial has only 2 extras, the line is straight, but the route toward the end of a line is different from the L1 trial since the predefined line area is serpentine. To reach the goal of the line, participants have to make two turns. The user study was designed to simulate situations such as like a cashier line at a shopping mall or check-in-counter at an airport. To simulate a crowded public space, we played ambient noise recorded at a shopping mall at 60 dB [49].

5.2 Procedure and Metrics

After obtaining the IRB-approved (the Ethics Review Committee on Research with Human Subjects of Waseda University, 2020-039) informed consent from participants, similar to the preliminary study (Section 3.2.2), we performed a 15-min pre-interview during which we asked about participants' daily experiences, challenges and confidence when standing in lines. We asked participants to rate a set of statements (Q1–Q7 in Figure 7) using a 7 point Likert scale (from 1, strongly disagree, to 7, strongly agree). Then we gave participants around 30 min of training before the main session. We also clarified that the technical phrase "target" meant the person to follow in the training session. Based on the previous feedback, where P2 found it difficult to hold the smartphone (A8), we applied a smartphone ring to the smartphone so that the user can easily maintain a constant system position. After the training, we conducted the main session, which took around 30 minutes.

To measure how accurately the blind user found the line, we measured the distribution of stop positions of the blind user when he or she found the line. As shown in Figure 8, we defined the area within a square of length 0.5 m as the *ideal position* when the blind user is standing in the center of a line and maintaining social distancing (1.5 m) from the person in front of them. We also defined the space around the ideal position (a total square of length 1.5 m), as *acceptable positions*. Every time a participant found the line, we added their stop position to the distribution. Every time the line moved, we added where the participant stopped to the distribution. While the experiment, we put tape on the floor and measured the actual stop positions referring to the tape.

After completing all the trials, we asked participants to answer a set of questions (the SUS [9] and Q1–Q9 in Figure 7) as well as open-ended questions to gather qualitative feedback. To observe how LineChaser improved the user experience when standing in line, we compared the results of the post-interview with those of the pre-interview. In total, the whole experiment took approximately 90 min per participant.

6 RESULTS

6.1 Past Experiences about Standing in Lines

All participants reported that their main strategy for finding the end of a line was asking someone, usually a stranger or a store clerk. Four participants (P06, P07, P11 and P12) clarified that they have no other way of finding the end of a line except to ask others for help. P02 and P07 reported that they hesitate to stand in lines on their own because they think a stand-in-line task will certainly cause them trouble: A11:*"It it difficult for me to both find and follow any line. I do not stand in lines by myself because it is troublesome."* (P07). Other than asking a stranger or a clerk, some mentioned that they find the end of a line by sensing positions of surrounding people by listening only in a familiar place (P04, P08, and P11). P09 mentioned that he video calls his family to determine where the end of a line is.

Eight participants reported that they complete the task of following a line mainly by asking a stranger to notify them when a line moves or by listening to ambient sounds. Two participants reported approaching strangers apologetically as: A12:*"When I ask a stranger to notify me each time the line moves, I feel sorry to have them help me for a long time."* (P05). Although one of their main skill is to use auditory senses, eight participants reported feeling that it is difficult to use auditory senses during the current COVID-19 pandemic. Not only are they required to cover their face with a mask (which dulls their auditory sense), but they must also to maintain social distancing with others, which prevents them from detecting a target from aural sensing. One participant commented: A13:*"I usually listen to ambient sounds or footsteps to follow a line. However, since the outbreak of COVID-19, my auditory senses has been limited by needing to wear a mask."* (P02).

6.2 Overall Performance

6.2.1 Stop Position after Finding the End of a Line. Figure 8 (a) shows the distribution of positions where participants stopped after finding the end of a line. All participants were able to successfully find the end of a line in all 66 trials. The success rate of finding a line at the ideal position was 40.9% (27 out of 66). In the other 59.1% (39 out of 66 trials), all participants successfully found the line within the definition of acceptable positions.

6.2.2 Time Took to Find the End of a Line. In L1 (straight line), the average time took to find the end of a line with two, three, four extras were 47.8s (SD: 18.0s), 49.9s (SD: 33.8s) and 41.7s (SD: 14.2s), respectively. For L2 (serpentine line), the corresponding times were 52.8s (SD: 15.6s), 55.8s (SD: 37.8), and 36.9s (SD: 13.4s). All participants tended to take more time to find the end of an L2, especially when it had only two or three people. This is mainly because they have to make 90° turn to the right once or twice to find the end of the L2 line.

6.2.3 Stop Positions when Following a Line. Figure 8 (b) shows the distribution of positions where participants stopped while following a line to the goal. All participants were able to successfully follow the line and reach the goal in all 72 trials. The success rate of following a line with the ideal positions was 34.8% (46 out of 132). Participants followed with acceptable positions 91.7% of the time (121 out of 132). For the other 11 trials, participants failed to stop within acceptable positions.

The 11 failure cases, in which participants did not stop in acceptable positions, occurred mainly due to four reasons: (1) P01, P07, and P08 were unable to correct her orientation; (2) P05 did not understand how to use the interface; and (3) P11 did not listen to the instructions. Reasons (1) and (2) were the causes of 10 failures in which participants stood behind the acceptable positions (*i.e.* , they stayed behind as the line moved forward). LineChaser vibrates to prompt forward movement only when the participant is facing the correct direction. Three participants were unable to face the correct direction and thus did not receive the vibration signal to move forward. Reason (3) was the cause of one failure in which P11 stood just behind the target. For the trial in which the navigation failed, P11 managed to stop just before colliding with the target because LineChaser issued an emergency stop signal. Also, in trials for P12, we observed a situation where ARKit accumulated a localization error and therefore instructed P12 to walk out of the line. The details of localization errors in ARKit are reported in Yoon *et al.* [57].

6.2.4 Comparisons between LineChaser and the Prototype System. Although P12 failed to follow the line movements with the prototype system (four trials out of six trials), when P12 used LineChaser, P12 was able to complete both tasks in all trials. P12 described the reason for her success as: A14:*"I was able to hold the smartphone stably compared to the preliminary study."* (P12). She also gave a higher SUS score for LineChaser (72.5, C+) than for the prototype system (37.5, F), and gave a positive comment: A15:*"The integration of the audio and vibration interfaces made me confident about facing the right direction. The new audio feedback gave me a rough image of the direction I should be facing compared to the prototype system."* (P12).

6.3 Subjective Ratings

Figure 7 shows the questionnaire results, which show that most participants felt more confident and comfortable standing in a line after the experiment (with the system) than before (without the system, their daily experience). We compared each question using the Wilcoxon signed-rank test with 1% levels of significance. The p-values of each test are shown in Figure 7. Our analysis revealed that, in Q1–Q5 except for Q6 and Q7, LineChaser received significantly ($p < 0.001$) better ratings than their daily experience. As shown by Q8 and Q9, the audio and vibration interface both received a high rating as no one rated both interfaces lower than 4 (neutral). Table 1 reports SUS scores [5] for each participant. The mean SUS score was 83.9 (SD: 10.1) which is an "A" rating on the SUS grade.

6.4 Qualitative feedback

All participants generally agreed that they were able to both find and follow a line by themselves with LineChaser: A16:*"I am very happy to be able to find a line without needing to touch anything [rails or strangers]. Also, I was confident that I would not bump into the target as the system notifies me with an emergency signal if I am too close."* (P03); A17:*"With this system, I can grasp my orientation and the distance to the target. Being able to grasp the distance is very important in the current situation [with regard to COVID-19]. Also, I am surprised that this system can specify the target."'* (P04); and A18:*"I felt that I do not need my cane anymore, as with this system I can maintain a certain amount of distance from the target. I think this system is revolutionary because I usually find a line by asking strangers, but with this system, I do not have to rely on others."* (P06).

We also received feedback from P10, who used LineChaser with a guide dog. Her positive feedback was: A19:*"I could both find and follow a line, while maintaining social distancing. Neither of these tasks are supported by my guide dog."* (P10). She indicated that some of the instructions for LineChaser should be improved: A20:*"The system gave me an instruction to slide left, but guide dogs does not have such commands as they are usually taught to keep left of the owner. I felt her being confused when I slid to my left. As I am pretty confident that I will not bump into anything with a guide dog, I only need information about the direction to the end of a line and distance to the target to maintain social distancing while following them."* (P10).

Most participants (P02, P03, and P06–P12) reported feeling that the integration of audio and vibration feedback was easy to understand: A21:*"The audio feedback gives me an approximate sense of the direction I should be facing. Then, I can find the exact direction with vibration feedback."* (P09). P10 also commented about difficulty getting used to the interface: A22:*" As I use this system I noticed that the tip for using this system is to move gently, not quick... Some people may have a hard time until they get the tip of it."* (P09).

Half of the participants (P04 and P08–P12) had a positive impression of the system because it was implemented on an off-the-shelf

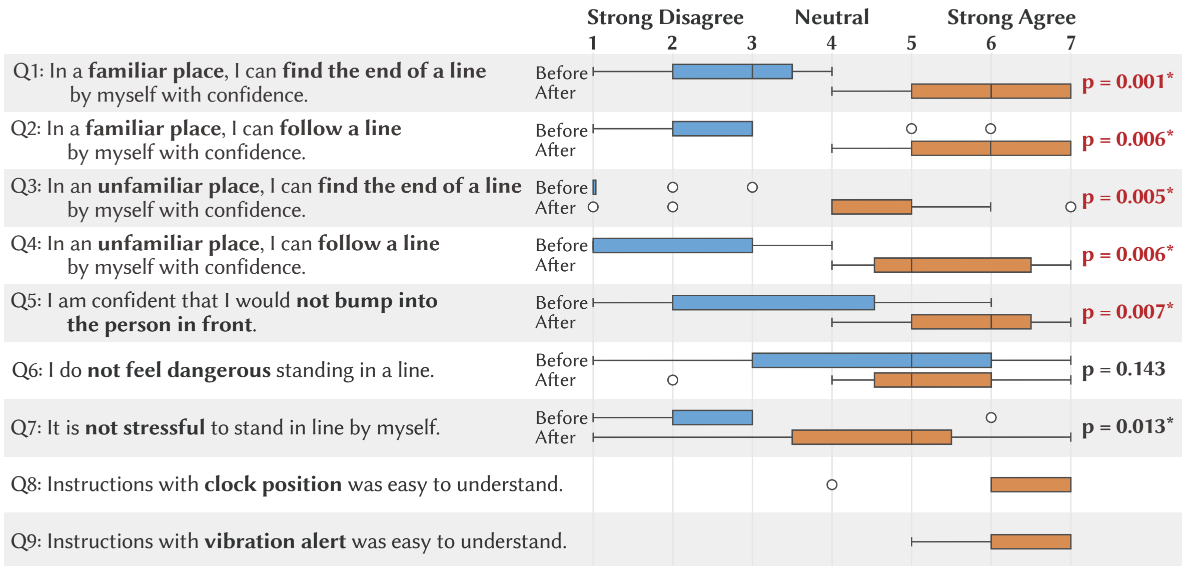

Figure 7: Likert scores and summary of the answers before and after the experiment. p is the value of the Wilcoxon signed-rank test done on each question (* indicates the significance found at the levels of 0.01).

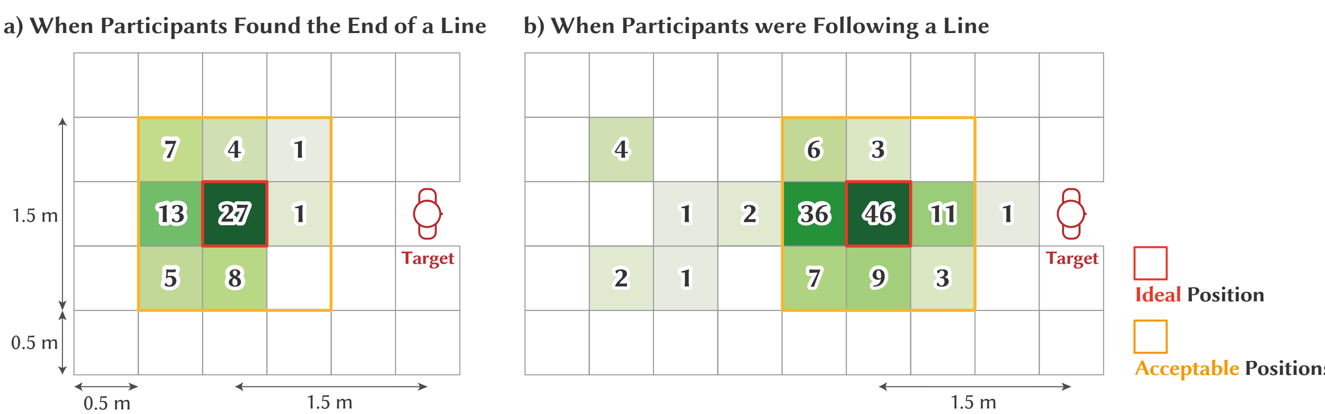

Figure 8: Stop positions while finding and following a line.

smartphone: A23: *"I am happy that this system allows me to follow a line with just a single smartphone."* (P08). However, 11 participants pointed out that the requirement to hold the iPhone so that the front camera faces others should be improved: A24: *"I could easily hold the iPhone, but I hesitate to hold it by facing the camera to others."* (P03); and A25: *"I prefer not to hold the iPhone like this because people might think I am raising my hand"* (P05). Also, two participants reported a physical burden of LineChaser: A26: *"The way of holding the iPhone was easier compared to the prototype system, but still heavy because I had to hold my hand up."* (P12); and A27: *"The method of holding the iPhone by using our left hand should be improved. We blind people prefer our hand to be free."* (P06).

7 DISCUSSION

7.1 Effectiveness of LineChaser

All participants reported that they constantly face difficulties where they do not know where the end of a line is and also when and how much the line moves while they are waiting in it (A11). They also reported that the social distancing norm since the outbreak of COVID-19 makes the situation more challenging than before because nearby people are farther away than the necessary distance for reliable auditory sensing (A13).

Although some users had various difficulties, LineChaser successfully enabled all participants to both find and follow a line. They all successfully found the end of a line at acceptable positions, indicating that LineChaser can navigate the blind user properly to the end of a line. LineChaser was also able to help blind users stop at acceptable positions 91.7% of the time while following a line (Figure 8 (a)). Feedback from the participants also supported the effectiveness of our system (A16–19). LineChaser received an SUS mean score of 83.9, which is rated as "A." All participants significantly increased most of their scores for confidence and comfortableness when standing in line (Figure 7).

7.2 User Interfaces and Training

In LineChaser, we adopted both audio and vibration for the user interface as audio feedback alone may be less effective in a noisy/crowded environment [8]. As a result, participants appreciated that using a double encoding of the same information with both audio and vibration can increase the understandability of the feedback (A21).

While the overall results are positive, we also found opportunities to improve the user interfaces. We observed a few cases in which the system did not provide a vibration to signal to prompt the user to move forward because of an incorrect device orientation due to the sensing capability of correct orientation (Section 6.2.3 (1)). Improved real-time guidance for device orientation may reduce such failures. In one instance, P11 did not notice the signal to stop (Section 6.2.3 (3)). Thus, we may need to redesign the signals to function better in noisy practical environments.

Another possibility is a user interface that adapts to the skill of user's navigation aid (a cane or a guide dog). As we observed from P10 (A20), improved instructions should be designed not only for cane users but also for guide dog users. Williams *et al.* [55] summarized that a cane is for obstacle detection and a guide dog is for obstacle avoidance. As guide dogs can naturally prevent collisions, instructions can be reduced by eliminating collision-related information. Instead, the system can provide more information about the surrounding environment. Additionally, P10 reported that some instructions are not appropriate for guide dogs (*e.g.* slide left), and it is necessary to conduct studies that focus on users of guide dogs and carefully redesign an optimized user interface for them.

For higher usability of the system, not only a redesign of interface is required but also training method to utilize the interface should also be considered. While all participants could learn how to use the system after a short training session (30 min), P01, P05, P07, and P08 experienced ten failures because they were not accustomed to the interface of the system (Section 6.2.3 (1) and (2)). Training is an imperative part of the efforts to make these technologies available for the blind community. We plan to collaborate with orientation and mobility training communities to design new training methods by seamlessly integrating new navigation technologies into their traditional navigation tools, such as canes and guide dogs [54].

7.3 Integration with Navigation Systems

Our ultimate goal is to supplement practical indoor navigation systems to allow blind users to stand in line in real-world environments. Various localization methods are proposed for helping the blind people navigate, but the methods based on the radio-wave signal strength (RSS) of Wi-Fi networks or Bluetooth beacons are used by the most practical systems [18, 32, 40, 44, 52]. Such systems can achieve an accuracy of 1.5m mean error at best, but this is not sufficient to navigate a user to an end-of-line location as LineChaser did. We used the AR marker-based localization (Section 4.1) that had a better localization accuracy compared with RSS-based systems [40, 44]. Overall, most of the components can be integrated into an RSS-based indoor navigation system, but the function for finding the end of the line requires higher localization accuracy. Possible solutions include integrating computer vision-based end-of-line recognition, improving RSS-based localization, and integrating AR marker localization. We plan to consult development teams for indoor navigation systems to plan a road map toward integration.

7.4 Real-world scenarios

We conducted experiments in a controlled environment. In real-world scenarios, there are varieties of situations that we can not simulate in a lab-based study. For example, a target person may bend down while following a line. In this case, LineChaser may not have the target person in the camera field of view and then misinstruct the blind user to move forward. In a case a line has groups of people standing together and occupy the same area of the line, the system recognizes the closest person in the group as the target. The closest person in the group may dynamically change, and the system will fail target identification. Therefore, we plan to conduct real-world user studies to assess the generalizability of LineChaser in various situations in real-world settings.

7.5 Social Acceptance

Although we obtained positive feedback on the fact that the entire stand-in-line task could be done with an off-the-shelf smartphone (A23), some participants stated that they would not use this system in public spaces, mainly due to the way that the smartphone must be held (A25). LineChaser was implemented on iPhone 11 Pro by facing the front camera to others. When considering how the system would fit with current uses' practice, the release of iPhone 12 Pro, which is equipped with Lidar sensor on the back, may have a positive impact on the problem with the way of how the smartphone is held.

Participants were concerned about pointing a camera explicitly at others (A24). While cameras and sensors of smartphones are being developed to provide more opportunities to support blind people, this problem is always present and may cause *social friction*. To reduce such social friction, alternative *seamless* wearable devices (*e.g.* smart glasses) may play an important role as a technical solution. We also should raise the societal awareness of the computer vision-based assistive technologies for the blind.

7.6 Ergonomics

Given the fact that we focus on off-the-shelf smartphones, it is not easy to improve the ergonomics of the system. We improved the device's graspability by adding a small handle to the smartphone after the prototype evaluation. P12 rated our prototype system with a SUS score of 37.5 (F) because she had a hard time holding an iPhone 11 Pro and she reported it was too heavy to hold for several minutes. However, P12 rated our improved system higher because the handle helped her grasp the device comfortably (A14). Overall, P12 was able to stand in line with high confidence with LineChaser. However, P12 still reported a physical burden of the system (A26), and P06 preferred to free their hand while using the system (A27). We observed that the ergonomics aspects, such as the way of gripping the device, greatly affects the usability of the whole system, and such aspects should be taken into account in the device selection phase for assistive technologies. For example, using wearable devices which are discussed in Section 7.5 could be one solution to this problem as it enables users to use the system with their hands-free.

8 CONCLUSION

This work developed a smartphone-based system that helps blind people to stand in lines. We first developed a prototype system that helps blind users follow the person in front of them as they move intermittently, and performed a preliminary study with six blind people. Based on the results and feedback, we designed LineChaser. LineChaser first guides a blind user to the end of a line and then helps the blind user follow the line. LineChaser uses the RGB camera to detect nearby people and the infrared depth sensor to estimate the distance to the target. LineChaser uses an audio interface to convey detailed navigation instructions and information on the distance to the target. A vibration interface prompts the blind user to move or stop. We performed a more advanced user study with 12 blind participants and observed that LineChaser enabled all participants to complete both tasks, while maintaining appropriate social distancing. We observed that LineChaser significantly increased their confidence in standing in lines. In the future, we plan to integrate LineChaser into a navigation system with high localization accuracy and a re-designed interface that is improved based on the results of real-word user study.

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