Orienting Kinesthetically: A Haptic Handheld Wayfinder for People with Visual Impairments

TOMOHIRO AMEMIYA
Nippon Telegraph and Telephone Corporation
and
HISASHI SUGIYAMA
Kyoto City Fire Department

Orientation and position information are vital for people with visual impairments if they are to avoid obstacles and hazards while walking around. We develop and evaluate a haptic direction indicator that delivers directional information in real time through kinesthetic cues. The indicator uses a novel kinesthetic perception method called the pseudo-attraction force technique, which employs the nonlinear relationship between perceived and physical acceleration to generate a force sensation. In an experiment, we find that the haptic direction indicator allowed people with visual impairments to walk safely along a predefined route at their usual walking pace without any previous training, independent of the existence of auditory information. The findings indicate that the haptic direction indicator is effective at delivering simple navigational information, and is a suitable substitute for and/or enhancement to conventional wayfinding methods.

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Authors' addresses: T. Amemiya, Human and Information Science Laboratory, NTT Communication Science Laboratories, Nippon Telegraph and Telephone Corporation, 3-1 Morinosato Wakamiya, Atsugi, Kanagawa 243-0198, Japan; email: amemiya@ieee.org; H. Sugiyama, Information for Fire and Disaster Prevention, Kyoto City Fire Department, 398 Higashiuratsuji-cho, Kamazadori shimodachiuri-kudaru, Kyoto 606-8265, Japan.

1. INTRODUCTION

One of the main factors preventing people with visual impairments from participating in society and being independent is the difficulty involved in walking from one place to another unaided. To travel independently, they must continually update their orientation and position to find their way and avoid obstacles and hazards. This can be stressful and dangerous, and can increase attentional load, especially in unfamiliar areas. Orientation and mobility are essential components of this functionality [Golledge 1992]. Orientation refers to the recognition of the spatial relation between the current and target locations, and mobility refers to the ability to move safely through space. The spatial relation is generally recognized by using various sensory clues to interact with the environment. However, orientation and mobility skills vary greatly among people with visual impairments [Foulke 1996]. In addition, for some people with visual impairments, these abilities may be disrupted when they take unusual paths in a quiet environment or when an unusual event occurs that disrupts their orientation sensing. For example, some have reported that they became disoriented after a fall when they could not find anyone to help them. Therefore, assistive technology devices designed to enable pedestrians with visual impairments to obtain orientation information would be very useful in assisting them in autonomic walking. An intuitive understanding of the orientation information is particularly important for all pedestrians with visual impairments who use assistive technology devices. If there is no need for any prior training or explanation of the meaning of the signals from the assistive technology devices, it will be less stressful, safer, and reduce the attentional load imposed on pedestrians with visual impairments.

In this article, we report an empirical study involving a navigation method for pedestrians with visual impairments that employs kinesthetic cues. This article is an extended version of a paper presented at the ACM SIGACCESS conference on Computers and Accessibility [Amemiya and Sugiyama 2009], and includes an evaluation of the performance of the proposed device, additional detail about the experimental design, an analysis of the experimental results, and a discussion of the impact of the type of disability on the perceived performance of the device to confirm its applicability.

2. RELATED WORK

Recent years have seen an increase in pedestrian navigation systems on mobile devices, such as mobile phones with a satellite positioning function, which employ different sensory channels (i.e., visual and/or audio channels). Unfortunately, people with visual impairments cannot use vision-based navigation aids. Therefore, many handheld auditory-feedback devices for people with visual impairments have been developed, such as Talking Signs [Crandall et al. 1999] or similar acoustic information output devices [Loomis et al. 2005]. Although such audio interfaces assist users to move in the right direction by providing sound cues, they can be problematic when they conflict with other sounds or speech around the users, leading to difficulties in distinguishing and interpreting the sounds generated by the system [Wilson et al. 2007]. In addition, pedestrians with visual impairments often rely on information contained within the ambient sounds for navigation purposes. Wearing headphones prevents them from hearing these ambient sounds thus making navigation less safe. Furthermore, auditory information cannot be used in noisy situations such as on busy city streets.

Tactile interaction may help overcome such navigation issues for people with visual impairments. It has been reported that tactile interaction can effectively assist pedestrians with visual impairments when crossing the street [Ross and Blasch 2000]. As tactile-based navigational aids, vibrotactile stimulation systems have been proposed using several vibrators in the shape of a cap [Cassinelli et al. 2006], rings [Amemiya et al. 2004], a vest [Erp et al. 2005], a belt [Heuten et al. 2008; Tan et al. 2003; Tsukada and Yasumura 2004], and a glove [Zelek et al. 2003]. Unfortunately, these tactile approaches require that users learn how to convert stimuli to information; this is not intuitive and requires training since the tactile stimuli employed are basically nondirectional.

A kinesthetic approach has the potential to be more intuitive and expressive than cutaneous (tactile) stimulation in conveying direction information since kinesthetic stimuli are directional. The intuitive comprehension of orientation information through the haptic modality is thought to be important in the situations we have outlined. We have proposed a mobile kinesthetic direction indicator for people with visual impairments based on a pseudo-attraction force method [Amemiya and Sugiyama 2008] and conducted a user requirements study of people with visual impairments [Amemiya 2009]. The fundamental technical design of the pseudo-attraction force method has already been published [Amemiya et al. 2005; Amemiya and Maeda 2009], and we outline this work in the following section.

In this article, we redesign and develop a new haptic direction indicator that guides users with visual impairments in the desired direction by the asymmetric oscillation of weights. In addition, we report an empirical study that involved 23 participants with visual impairments and evaluated the feasibility of a system based on the haptic direction indicator.

3. APPROACH

Our approach is to apply the pseudo-attraction force technique to present a persistent pulling or pushing sensation in mobile devices. The mechanism for creating a pseudo-attraction force has to be small enough to fit into a handheld device and have sufficient angular resolution for force presentation on a two-dimensional plane. In this section, we outline the pseudo-attraction force technique, show the prerequisites for designing a haptic direction indicator for pedestrians with visual impairments, and describe a prototype that implements the technique.

3.1 Pseudo-Attraction Force Technique

The pseudo-attraction force technique exploits the characteristics of human perception to generate a force sensation in mobile devices. In the technique,

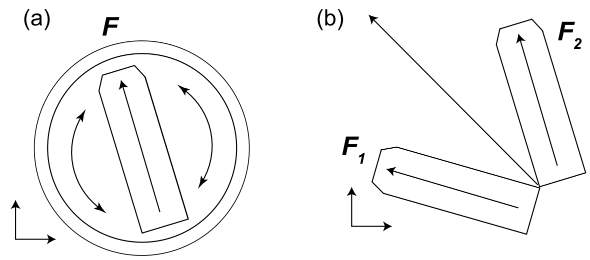

Fig. 1. Two-dimensional force vector. (a) Turntable approach: one module with rotational mechanism. (b) Vector summation approach: linear independent vector modules.

different acceleration patterns are generated in opposing directions to create a perceived force imbalance and thereby produce the sensation of directional pushing or pulling. Concretely, a strong acceleration is generated for a very brief time in one direction, while a weaker acceleration is generated over a longer period of time in the reverse direction. Human haptic sensors cannot detect the weaker acceleration, so the original position of the mass is washed out. The result is that the user is tricked into perceiving a unidirectional force. This force sensation can be made continuous by repeating the motions (See Amemiya and Maeda [2008] and Amemiya et al. [2008] for details). To generate the asymmetric back-and-forth motion of a small, constrained mass, we adopted a slider-crank mechanism.

3.1.1 *Design of Two-Dimensional Force Display.* We previously developed a prototype of a two-dimensional force display; one module based on the slider-crank mechanism was mounted on a turntable. The direction of the force display module was set by driving the turntable with a belt drive system (Figure 1(a)). Turntable rotation, however, took considerable time, which means that immediacy was lost. A two-dimensional force can be generated not only by rotating a single force display module but also through the summation of linearly independent force vectors. Therefore, the angular resolution performance of participants with visual impairments was assessed using eight-step (compass) and twelve-step (clock position) configurations. The results showed that eight-step force presentation offered better resolution, indicating that presenting a force vector in eight cardinal directions would be enough for designing a two-dimensional force display [Amemiya 2009].

We fabricated a haptic direction indicator to generate a force sensation in at least eight cardinal directions by the summation of linearly independent force vectors, as shown in Figure 1(b). Four layers, each containing a single module, were stacked to create the force display. By combining the force vectors generated by each module, the force display can create a force sensation on a two-dimensional plane more quickly than the turntable approach.

3.1.2 *Design of Hybrid Mechanism.* Figure 2(a) shows the mechanisms used in the previous prototype. Because of the length of the linkages, especially linkage *CD* (rod), the overall length of the mechanism tends to be large at about 175mm [Amemiya and Maeda 2008, 2009]. In addition, the previous

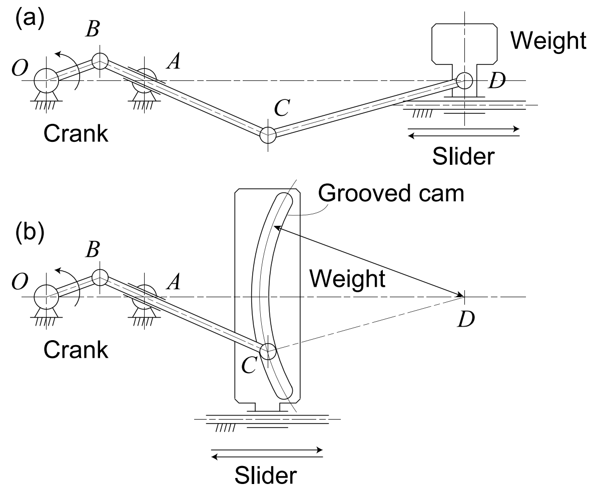

Fig. 2. (a) Previous mechanism for generating asymmetric oscillation and (b) proposed mechanism, which is the equivalent mechanism of (a), but with the *CD* length decreased to virtually zero.

prototype used a pinion gear and crown gears, whose axes were relatively displaced, to drive the crank. The relative displacement of the gear axes caused gear noise, which annoyed the users. In fact, many people, including people who are blind, who have held the prototype [Amemiya and Maeda 2009] have complained about the noise.

Figure 2(b) shows the new mechanism, which is the mechanical equivalent of the previous one. As in the previous mechanism, a circular motion at a constant speed (crank *OB*) is transformed into a curvilinear motion by a swinging-block slider-crank mechanism. The end point on the curvilinear motion (point *C*) slides along a cam line, whose shape is a circular arc with radius *CD*, where point *D* is the center of the arc. Therefore, the proposed mechanism produces the desired reciprocating motion with asymmetric oscillation. Note that this mechanism has only a single degree of freedom (DOF).

3.2 Implementation

On the basis of the designs described above, we stacked four hybrid modules as shown in Figure 3. Each module represents one of the four cardinal directions with each directional signal being generated using one motor. By using the sum of the generated vectors, which are linearly independent, the force display can create a force sensation in the eight cardinal directions on a two-dimensional plane.

The asymmetric oscillation (**F**) is given by

$$\mathbf{F}(t) = \sum_{j=1}^{n} m_j \frac{d^2 x_j(t)}{dt^2} \mathbf{e}_j, \qquad (1)$$

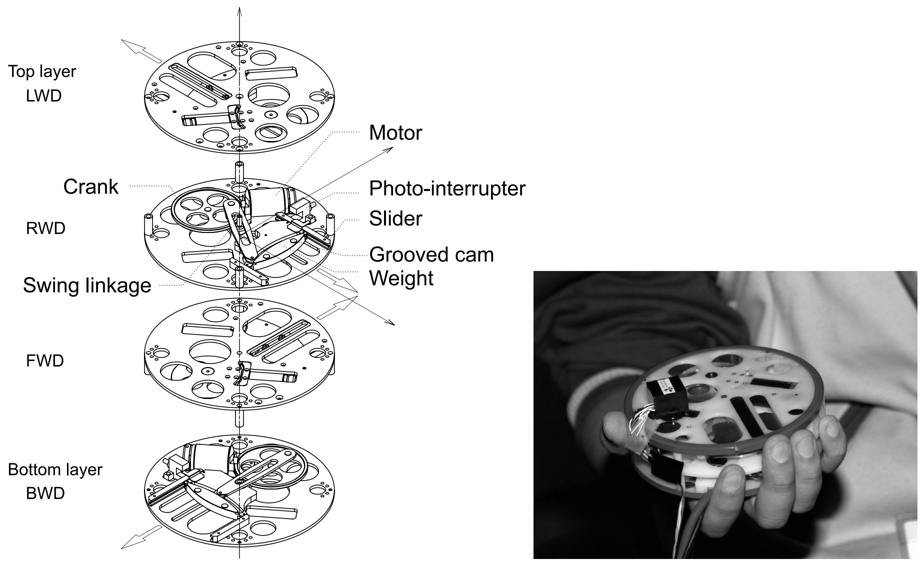

Fig. 3. Structure of the new prototype for generating pseudo-attraction force on a two-dimensional plane. One unit can have four modules. A hybrid configuration of the swinging slider-crank mechanism; the cam mechanism in each module generates asymmetric acceleration.

where m_j is the weight in module No,*j*, n is the number of modules, and $\ddot{x}_j$ is the acceleration generated by module No.*j*. The acceleration $\ddot{x}_j$ is given by the second derivative with respect to time of the motion of the weight x_j. The equation for the motion of the weight in module No.*j* is

$$x_j(t) = l_1 \cos \omega_j t \ + \ \mu_j \left(d - l_1 \cos \omega_j t\right) \\ + \ \sqrt{{l_3}^2 - \left\{l_1 \left(\mu_j - 1\right) \sin \omega_j t\right\}^2}, \quad (2)$$

where

$$\mu_j = \frac{l_2}{\sqrt{{l_1}^2 + d^2 - 2\, l_1 d \cos \omega_j t}}, \quad (3)$$

and $x_j(t) = OD$, $d = OA$, $l_1 = OB$, $l_2 = BC$, $l_3 = CD$, and $\omega_j t = AOB$, see Figure 2. ω_j is the constant angular velocity, and t is time. In the prototype, d = 28mm, l_1 = 15mm, l_2 = 60mm, l_3 = 70mm, and n=4, and the unit vectors are $\mathbf{e}_j \cdot \mathbf{e}_{j+1}$=0, $|\mathbf{e}_j|$=1. All m_j and ω_j are identical, m_j = 40 g, $\omega_j/2\pi$ = 5 Hz.

In the prototype, the output shaft of each motor (DC 6.0V, 2232R006S; Faulhaber) is mounted in a roller made of nylon. The roller drives the crank wheel by friction. The external diameters of the motor roller and the crank wheel are 4mm and 44mm, respectively. The reduction ratio is basically 1:11, but it changes slightly as a result of changes in such factors as temperature. The display weighs approximately 430g. The diameter of the base is the same as that of a compact disc (i.e., 120mm). The force display is 36mm thick. Each weight on the slider is equipped with a photo-interrupter (PM-R24; SUNX Ltd.) to detect its position and velocity. The speed of each crank is stabilized at 5

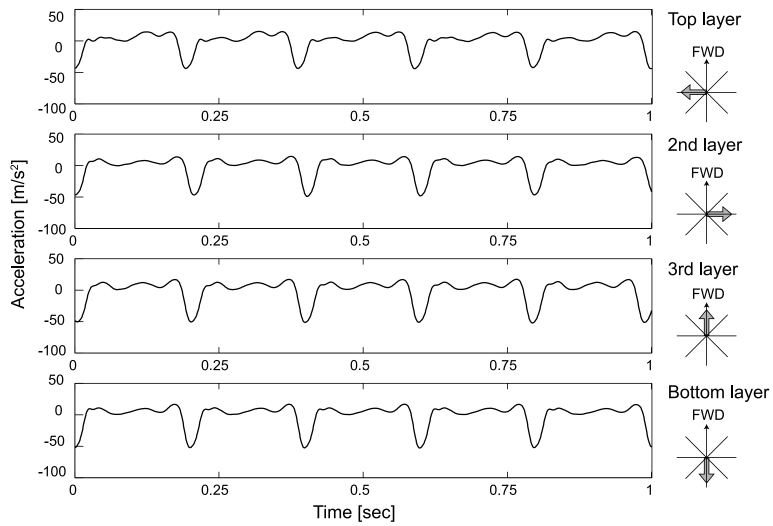

Fig. 4. Actual acceleration profile calculated from the position data measured by a laser sensor; processed by a seventh order LPF Butterworth filter with a cut-off frequency of 100Hz.

counts per second by closed feedback loop control (P control) so that the signal intervals of the photo-interrupter are close to 200ms. When combining two orthogonal force vectors, the phases of the cranks are synchronized by closed feedback loop control (PID control) so that the onset intervals of the photo-interrupters are close to zero.

3.3 Performance Evaluation

Figure 4 shows the measured acceleration profile generated by the device at 5 counts per second. Actual acceleration values were calculated by the position data of each weight which were acquired by a laser sensor (Keyence Inc., LK-G150, 10kHz sampling) with the bottom of the device fixed to a base. The acceleration profile of the top layer differed slightly from the others due to its distance from the fixed base. The effect of oscillation was augmented by the principle of leverage, leading to some degree of measurement error. The acceleration amplitude reached about 50% of the theoretical acceleration peak. We assume that our friction drive mechanism transmitted less torque than the previous gear drive.

Figure 5 shows examples of the response profile of phase synchronization. The onset intervals between pairs consisting of two orthogonal modules were acquired from the photo-interrupters when the bottom of the device was fixed to the base. An onset intervals of zero means that the two orthogonal modules are synchronized. The phases were synchronized and locked within 5 seconds, which showed that the force display created a force sensation in the eight cardinal directions on a two-dimensional plane.

A psychophysical pilot study revealed that people who held the force display clearly sensed a directed force. Five people without visual impairments (three

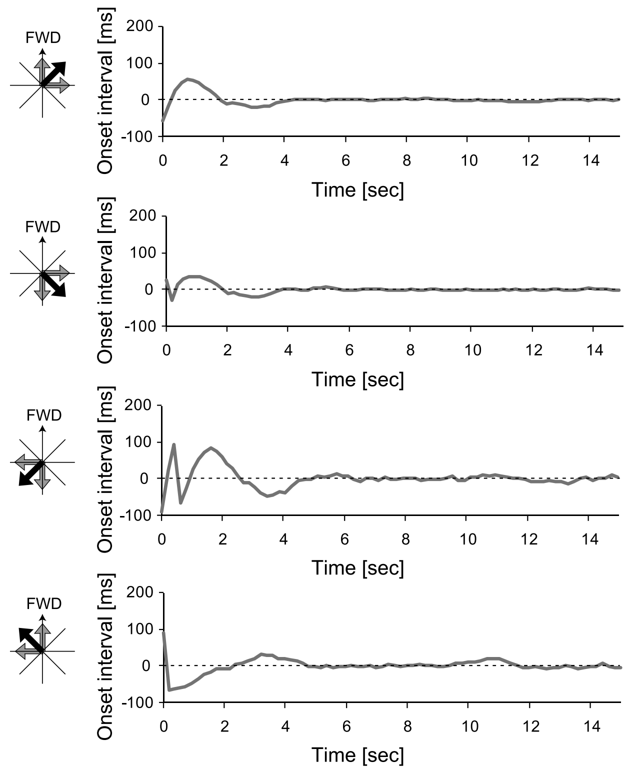

Fig. 5. Examples of the measured phase synchronization responses for combinations of each module. The onset intervals of the photo-interrupters were controlled so that they were close to zero by changing the angular velocity of the motor in the force display.

right-handed men and two right-handed women, aged 22–34 years), who were paid volunteers, participated in the pilot study. None of the participants had any previous experience with force displays or force display prototypes. They were required to reply with one of eight cardinal directions after a 5-second oscillating stimulus (north was defined as 0 degrees and the forward direction, and east as 90 degrees and right) without any prior training. Each participant experienced eight conditions × five trials, making a total of 40 trials (randomized). Visual and auditory effects were suppressed by having the participants wear eye-masks and ear muffs. The scatter pattern of "being pulled in the crank-to-slider direction" responses and the stimuli are shown in Figure 6. In general, the circles (responses) were grouped along the identity line. This indicates that the force display provided a well-perceived directed force sensation (pseudo-attraction force sensation) even though the measured acceleration peak was only half the expected value.

The sound pressure level of the noise generated by the device was measured in an anechoic room at NTT Communication Science Laboratories. A sound level meter (Rion, Inc., NL-31 Class 1) was used to measure the noise as determined by the A-weighted sound pressure level (SPL). The sound level meter

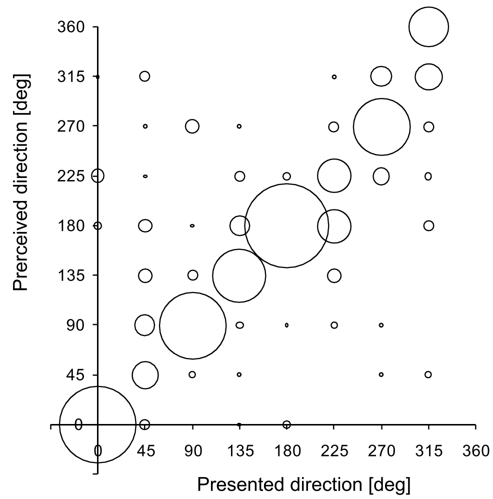

Fig. 6. Scatter pattern of the responses of five sighted participants as a function of the stimuli (a psychophysical pilot study). Stimulus and response of 0 degrees defined as the forward direction. The radii of the circles are proportional to the number of responses.

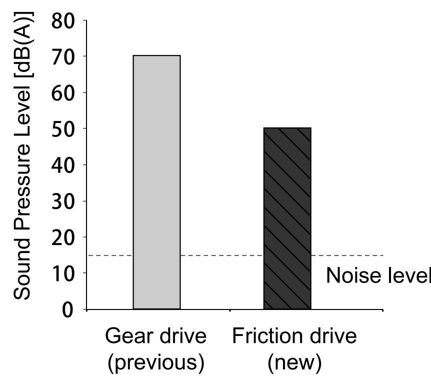

Fig. 7. Measured noise level. The proposed mechanism produces less noise than the previous mechanism. The dotted lines indicate the environmental noise level in an anechoic room.

was fixed to a tripod at a height of 1.0m from the ground and 30cm from the device. Figure 7 shows the measured noise SPL generated by the device at 5 counts per second. The gear drive of previous prototypes made the noise level exceed 65dB(A). With the friction drive of the new prototype, the noise level did not exceed 50dB(A) which shows that the friction drive emits much less noise.

4. EXPERIMENT

We performed an experiment related to predefined route guidance using the force display. We measured the time required to complete a walking task, the level of ease and the user expectation of the guidance on a subjective scale, and

Fig. 8. Overview of a model simulating Kyoto city, which has a checkerboard design of streets and avenues. The walls are foam sheets.

collected user feedback. We built a human-size maze in the gymnasium of the Kyoto Prefectural School for the Visually Impaired, Japan (Figure 8). Since the streets and avenues in Kyoto are mainly laid out in a grid, the maze was designed to offer checkerboard-shaped routes.

4.1 Participants

There were 23 visually impaired participants, 19 males and 4 females, who were volunteers from the Kyoto Prefectural School for the Visually Impaired. Ages ranged from 17 to 62 years (average 30). Thirteen are totally blind, and the other ten are partially sighted. Table I is a list of the characteristics of the participants' vision loss. The participants all reported that they had no irregularities with their hands in terms of tactile perception at the time of the experiment, and they were all untrained. Moreover, they were all ignorant of the purpose of the experiment. The research protocol was approved by local ethics committees. All participants provided written informed consent prior to testing.

4.2 Apparatus

The compact-disk-sized force display described in Section 2 was used. To measure the yaw angle of the force display, a motion sensor (MDP-A3U9S; NEC TOKIN Corp.) was attached. Motors in the force display were powered by a 12V battery (ENAX) and controlled by an additional custom-built controller switch. The microprocessor (PIC18F252; Microchip Tech. Inc.) in the controller was connected to a portable computer (OQO model 02; OQO Inc.) via a USB port. Bluetooth 2.1 allowed the portable computer to communicate with the remote computer (ThinkPad X60s; Lenovo) within 100 meters. Since the global positioning system (GPS) did not work inside the gym with satisfactory accuracy, we used nine infrared sensors installed at the corners of the maze as a local positioning system; they were connected to the remote computer. To

Table I. Details of the Participants

Participant	Disability	Gender	Age	Grade of visual disability	Use of cane	Experimental order
1	Innate	Male	17	1	Yes	3
2	Innate	Male	19	1	Yes	4
3	Innate	Male	20	1	Yes	7
4	Innate	Male	20	1	Yes	9
5	Innate	Male	18	1	Yes	17
6	Innate	Male	34	1	Yes	19
7	Innate	Male	37	1	Yes	22
8	Innate	Male	42	1	Yes	23
9	Innate	Female	21	1	Yes	6
10	Acquired	Male	62	1	Yes	10
11	Acquired	Male	17	1	Yes	12
12	Acquired	Male	30	1	Yes	14
13	Acquired	Female	19	1	Yes	5
14	Innate	Male	18	2	Yes	13
15	Innate	Female	17	2	Yes	15
16	Innate	Male	50	2	Yes	18
17	Acquired	Male	27	2	No	2
18	Acquired	Male	57	2	No	11
19	Acquired	Male	44	2	No	21
20	Acquired	Female	57	2	No	1
21	Acquired	Male	25	4	No	20
22	Acquired	Male	18	5	No	16
23	Innate	Male	21	6	No	8

In Japan, people with disabilities, who have received a certificate from a local public body, are divided into several grades. Visual disabilities are divided into six grades defined by visual acuity and the size of visual field. Grade 1 is the most severe. Roughly, grade 1 is defined as totally blind, and grade 2 is severely low vision.

produce white noise, a clip-shaped music player (iPod shuffle 2nd generation; Apple Inc.) and noise-canceling headphones (Quiet Comfort 3; Bose Corp.) were used. Figure 9 shows the system configuration. The human-sized experimental labyrinth was formed with a series of foam panels (1,800mm × 900mm) occupying a space of 9m × 15m. The pads were soft enough not to cause injury in collisions.

The route and the journey duration were automatically logged by the system with infrared sensors placed at the corners of the walls, captured by digital video cameras from the second floor (about 4m from the ground), and manually noted on a sheet by the experimenters.

4.3 Procedure

A participant holding the haptic directional indicator was brought to one of three different departure points (S1, S2, or S3) in the labyrinth. No participants underwent any prior training. Participants who usually used a cane when walking held a cane with one hand and the haptic direction indicator with the other. Others held the haptic direction indicator with the dominant hand. They carried a small shoulder bag, which contained a notebook computer, a custom-build circuit, and a battery. An experimenter walked behind the participant to ensure his/her safety.

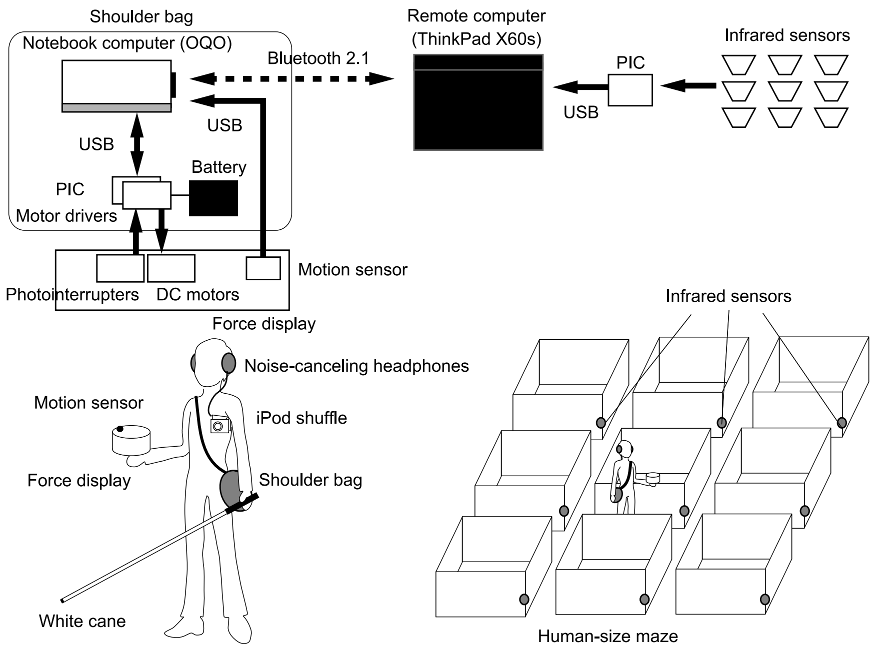

Fig. 9. System configuration of experiment. The participant held the force display with one hand and carried a small shoulder bag that contained a notebook computer with a custom-build circuit. The notebook computer was wirelessly connected to the remote computer which received information from the infrared sensors.

First, the force display presented a sensation of pushing forward. The participant then started walking from the departure point. The participant was guided by the force display to turn left or right at a certain turning point (nine points shown in Figure 10). At that point, the infrared sensor detected the arrival of the participant. In response, the remote computer connected to the infrared sensors sent the turn instruction to the notebook computer in the participant's bag. The direction of the force vector (go straight, turn left or right) was initially determined by the predefined route at each turning point and was automatically updated to one of the eight cardinal directions according to the orientation of the participant. In a similar way, they were then guided to the second, third, and fourth turning points and, finally, to the destination point. Experimenters indicated that the destination was reached after the participants had arrived at the destination point (S1, S2, or S3). The force display was always "on" during the navigation. If the participant made a wrong turn (and was about to begin walking the wrong route), the experimenter changed the direction of the haptic stimuli manually to return the participant to the predefined route and sent it via the remote computer (called "revision"). The same haptic stimuli for the eight cardinal directions were used for the revision. Nevertheless, if this correction failed or the participants did not notice the stimulus change, the experimenter walking behind intervened by touching their backs, giving verbal information about the correct turn and taking note

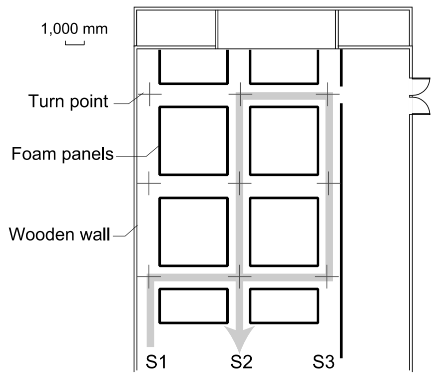

Fig. 10. Spatial layout of the gym and route example in the experiment. Participants were guided from the departure point to the first turning point. They were then guided to the second, third, and fourth turning points. Finally, they were guided to the destination point.

of any incorrect actions (called an "interruption"). Note that the participants were made aware of a wrong turn in an interruption but not in a revision. The participants had to go back one block to return to the correct path when there was an interruption.

4.4 Tasks

The navigation task consisted of walking predefined routes in the human-size maze under two auditory information conditions (audio masked and audio unmasked). Under the audio masked condition, all the audio information was masked by noise-canceling headphones with white noise. Under the audio unmasked condition, the participants were able to hear ambient sounds, but no artificial sounds were presented. We expected that people with visual impairments would utilize ambient audio information to identify obstacles or walls in front of them. Since the foam panels along the route were 900mm high, the audio cues would be different from those provided when walking along an ordinary hallway. However, the height of the wooden wall forming part of the building (on the left in Figure 10), was over 5 meters, and it provided a clear acoustic echo that assisted localization. Figure 11 overviews the experiment.

From the viewpoint of safety, we had the participants perform the task under the audio unmasked condition first. Each participant completed one trial under each of the two conditions. All predefined routes were determined so that the departure and destination points were incongruent, and there were four turns. The routes were different for the two conditions and were randomly selected to reduce the learning effect, for example, to prevent the distance to a turn being remembered or guessed. The participants were instructed to walk as fast and as accurately as possible.

All participants were invited to complete our two-item questionnaire and to provide feedback after the experiment. The statements were presented in a different randomized order for each participant. Each statement was rated by

(a) Condition: auditory information not masked

(b) Condition: auditory information masked by noise-cancellation headphones and white noise

Fig. 11. Overview of the experiment.

the participants on a 7-point Likert scale, with −3 meaning “totally disagree” and +3 “totally agree”. The questions were:

Q1. The guidance was easy to understand.

Q2. I expect it would be useful in disaster situations.

Our intention with Q1 was to gain some insight into the usability of the force display in the experiment. The aim with Q2 was to gain some insight into the feasibility of using it during disasters such as in heavy smoke (non-visual) or when there is siren noise (nonaudio). In Q2, the experimenter explained that a “disaster” meant a typical situation that lacked some visual and/or audio information, and which required quick and safe directional navigation. These questions focused on obtaining a subjective rating of the understandability and reliability of the system. In addition, the participants were invited to comment freely about what they felt during the task.

5. RESULTS

5.1 Failures and Recovery

Overall, our proposed system successfully enabled the participants to follow predefined routes. Twenty-one of twenty-three participants (91%) successfully completed the navigation task (i.e., walking from the entry point to the endpoint with four turns) under both conditions. Note that revised trials were also counted as successes whereas interrupted trials were counted as failures. The same two participants (#9 and #23) failed to complete the tasks under both conditions. The experimenter intervened (i.e., interruption) twice under the audio masked condition and three times under the audio unmasked condition. No other participants required intervention during the navigation task. Specifically, participant #9 always seemed to judge left stimuli as right stimuli, and participant #23 interpreted right stimuli as left stimuli. This tendency appeared to prevent the two participants from returning to the predefined route even if the stimuli were changed manually.

Seven participants under the audio masked condition and six participants under the audio unmasked condition failed to perceive the force sensation indicating a turn. Two of them could not recover the route at all until the experimenters intervened as described above (i.e., interruption). All of the participants other than the aforementioned two were able to recover the route when the force display was driven by the experimenter (i.e., revision). Under the audio masked condition, five participants made five mistakes. Under the audio unmasked condition, four participants made five mistakes. The average time required to recover from an incorrect turn was about 5 seconds, and the longest time was about 10 seconds.

5.2 Walking Pace

Since the travel distances differed across the trials, the walking pace was used as a measure of time to completion. The average length of the course was 31.3 meters under the audio unmasked conditions and 32.6 meters under the audio masked conditions. It took 66 seconds to walk the course under the audio unmasked conditions and 67 seconds under the audio masked condition on average. Figure 12 shows the walking pace under the two conditions. There was no significant difference in the walking pace under the two conditions ($t(20) = 1.16$, $p = .26$, *n.s.*; two-tailed pair-wise t-test), which means that the absence of auditory information did not affect the navigation performance. However, the result might be affected by the learning effect because of the order in which the conditions were presented, although we tried to reduce it.

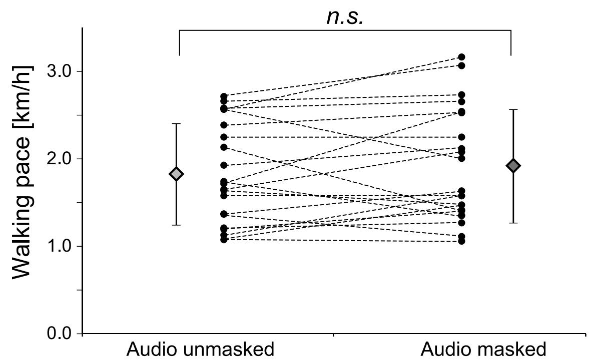

Fig. 12. Impact of audio cues on walking pace. Each dot indicates a participant's data point. Each open diamond indicates the average, and the error bar is the standard error of the mean.

The participant's walking trajectory captured by digital video was converted by projective transformation with the following equations offline:

$$x = \frac{h_1x' + h_2y' + h_3}{h_7x' + h_8y' + 1} \tag{4}$$

$$y = \frac{h_4x' + h_5y' + h_6}{h_7x' + h_8y' + 1}, \tag{5}$$

where (x, y) represents transformed values, and (x', y') are the values of the captured image. The four coordinate values for the transformation were manually selected, and projective transform matrix H was calculated as

$$H = \begin{pmatrix} h_1 & h_2 & h_3 \\ h_4 & h_5 & h_6 \\ h_7 & h_8 & 1 \end{pmatrix}. \tag{6}$$

The position of the participant was also selected manually and converted using H. Examples of the participants' trajectories are shown in Figure 13. The position was calculated every 30ms.

To compare the impact of visual disability type on navigation performance, the participants who completed the navigation task were divided into four groups according to disability type (innate/acquired) and by grade of disability (blind/low vision). Figure 14 indicates the average walking pace difference for participants #1 to #20 (except for participant #9 who did not complete the navigation task); we also excluded participants #21 to #23 who have a mild degree of low vision (the grade of disability is 4 or more) since the rest of the participants had a much more severe vision loss. We decided to make a distinction only between participants that were grade 1 (which is defined as totally blind), and grade 2 (which is defined as low vision). A two-way (group × audio masked condition) repeated measures analysis of variance (ANOVA) of the walking pace was performed. The results revealed no significant impact of the audio masked condition (F(1,30)=.89, p=.77, *n.s.*). The main effect of the participant groups (F(3,30)=2.67, p=.07, *n.s.*) was not significant, which indicates

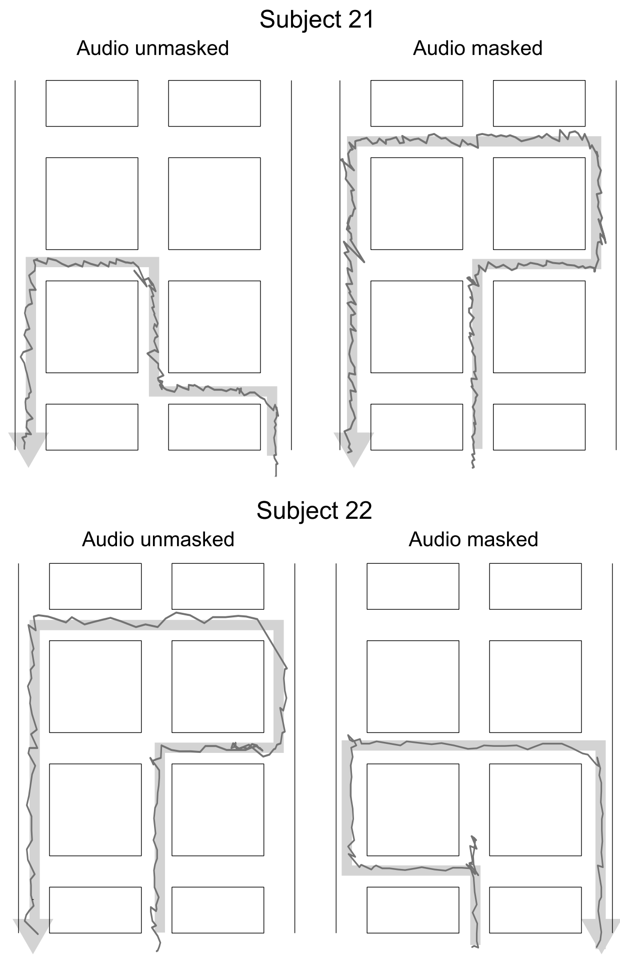

Fig. 13. Examples of participants' walking trajectories captured by digital video.

that the walking pace of people with visual impairments from various backgrounds is very similar. No significant interactions were observed ($F(3,30)=.98$, $p=.96$, *n.s.*).

There was no clear gender-related difference in the walking pace seen in the experimental results, although there was a substantial imbalance in the gender distribution. By investigating additional female participants, we will be able to argue the effectiveness of the system in relation to gender.

5.3 Subjective Rating

Almost all the participants rated both statements highly. The medians of the questionnaire results were +2 and +2. The quartile ranges were 1 and 1. No outliers were observed.

Moreover, we analyzed the questionnaire results very conservatively by considering only the high scores ("+2" or "+3") for each statement as indicating the

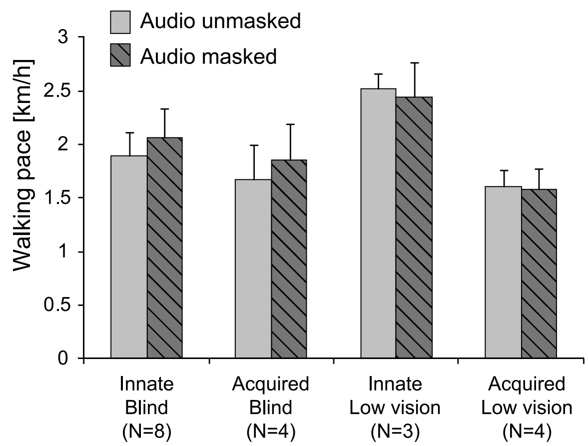

Fig. 14. Impact of type of visual disabilities on average walking pace: standard error shown.

usefulness; in other words, the 7-point questionnaire responses were converted into a binary response ("high score" or "not high score"). The scientific motivation for this is that we wanted to perform an analysis that only took account of people who felt strongly about the usefulness of this force-based navigation. By chance alone, the probability of a high score is 2/7. The ratings for the two statements have frequencies that are much higher than would be expected by chance (21 and 18, respectively, out of $N = 23$, with corresponding $p<.0001$ and .0001, using the binomial distribution).

Some participants commented after performing the task that they felt the device to be very useful and easy to comprehend. A negative comment from one participant was that his hand felt numb because of the vibration and weight of the force display. Another negative comment was that it was hard to keep the force display horizontal and to maintain the direction indicated by the display for a long period of time.

6. DISCUSSION

The results we have presented provide clear evidence of the usefulness of force-based navigation for people with visual impairments. Circles (A) and (B) in Figure 15 show that the participant could recover the intended original route by employing the force display. However, some participants collided with the walls as shown by circles (B) and (C) in Figure 15. The prototype had no function for the recovery of a straight path for walking. Due to the lack of such a function, the participants' direction tended to diverge from the center line after they had turned a corner which caused collisions after a long distance had been covered. To avoid such collisions, haptic signals for mid-course corrections are required. There is a trade-off between increasing the number of haptic signals and intuitive comprehension (or mental load), which is a version of the haptic "icon" problem [Enriquez and MacLean 2008]. Nonetheless, this should be considered in future systems. Our proposed system would also benefit from information displays for other sensory modalities. For instance, the addition

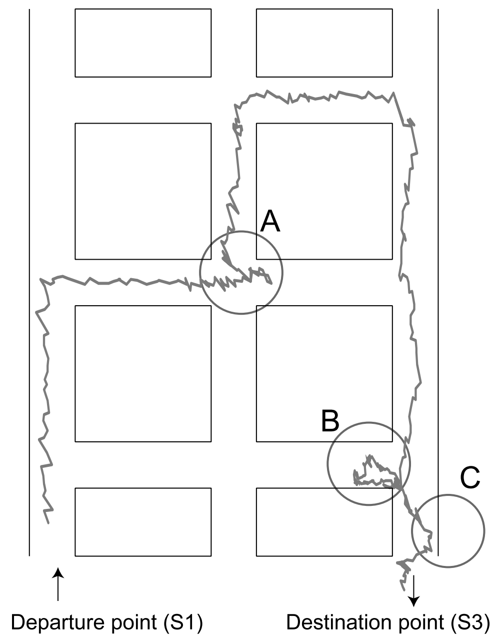

Fig. 15. Example of a participant's walking trajectory captured by digital video. Circles B and C indicate collisions caused by the absence of a function enabling the participant to recover from meandering.

of an audio navigation aid has the potential benefit that it can relatively easily provide complex and semantically rich information, such as categories of landmarks and street names. This semantic richness and complexity is very difficult to achieve with just a force display. Ross and Blasch pointed out that the combination of speech (auditory) and tapping (tactile) information would be useful as orientation aids [Ross and Blasch 2000]. Future work will include investigating the effect of such additional meaningful audio information. In pedestrian navigation, most sighted users rely on directional information, street names, and landmarks [Bradley and Dunlop 2005]. To reach their destination, they depend mainly on directional information which is used at key decision points (e.g., at turns). Our haptic navigation system can easily be expanded to support sighted pedestrians. In particular, travelers with a different mother tongue visiting an area would reap significant benefits because haptic navigation is nonverbal. The proposed system would also enable users with reading disabilities to travel independently. Iconic symbols such as left or right arrows would be sufficiently clear and accurate to indicate directions. However, haptic cues not only indicate direction (at the sensory phase) but also make bodies move directly (at the motor phase), which requires less response time. Therefore, haptic cues would be more suitable for navigation applications. Future work will include the integration of satellite navigation instruction which would expand the available area of our technique.

Changing the force vector manually assisted participants who made a wrong turn to return to the original route. Since the haptic stimuli were identical for the automatic and manual operations, one of the main reasons manual intervention was required was the incomplete algorithm for changing the direction of the force vector. The algorithm depended on the accuracy and reliability of the local position sensors (infrared sensors placed at the maze corners). The detection onset for the local position sensors and turning a corner varied as the walking pace changed. Our experimental system did not measure the walking pace of the participants which may have sometimes led to the failure to turn a corner. In the future, all systems will work without manual operation if they are implemented with precise positioning and rerouting technologies.

Our experimental setup has some limitations with regard to generalizing the findings for all areas of pedestrian navigation since we only examined a 90-degree change of direction. Since most streets and avenues, with the exception of certain cities such as Kyoto, are not laid out in a grid, a navigation task in relation to complicated routes must be the next step. In addition, we have to clarify whether the same angular resolution (i.e., the eight cardinal directions) is sufficient for arbitrary routes, in particular when avoiding obstacles. Pielot et al. have reported deficiencies in the human perception of body orientation when small angles are involved [Pielot et al. 2008]. Our previous study [Amemiya 2009] also showed that there is a systematic error with respect to the human perception of force orientation among people with visual impairments when they are not moving, which is less than 15 degrees when the force vector is provided in eight cardinal directions. A dynamic exploration of the force vector would be useful when walking complicated routes, which is similar to the guidance a human or a guide dog might provide and depends on the active or passive perception of haptic feedback while walking. Therefore, the systematic error could be minimized with a closed feedback loop, leading to precise routing. However, debate continues about the best way to understand the user's orientation for dynamic exploration and about the most suitable part of the body to which to attach the orientation sensors. Moreover, we must consider whether the force display should be held in the hand, carried in a bag, or worn. Not only the way of attaching the orientation sensor but also that of the force display should be considered, such as holding it by hand, carrying it, or wearing it. Also, it would be effective to remodel the hardware while combining the vector summation approach with the turntable approach (Figure 1) to present a more precise directional force and compensate for the deficiencies of each approach.

In the experiment, the force display always generated force during navigation, because in a pilot study we received feedback that the absence of stimuli made the participants anxious. However, it is well known that continued vibration tends to cause perceptual fatigue (i.e., adaptation) if it is presented for too long, as with all other sensations [Coren et al. 2003]. Nevertheless, there were no differences in the number of collisions with the walls between the L-shaped walking paths of the same trial: one is from the entry point to the second turn, the other is from the second to the last turn to the exit point. The average numbers of collisions were 0.10 and 0.12 (unmasked audio condition), and 0.07

and 0.09 (masked audio), respectively. The average lengths of the former and latter paths were 11.2 meters and 13.2 meters (unmasked audio), and 9.4 meters and 14.2 meters (masked audio), respectively. In addition, all but one of the participants reported that they did not feel any subjective perceptual difference between the start and the end as mentioned above. We conjecture that the effect of vibrotactile adaptation may not appear during short-term navigation, since the asymmetrically oscillating stimuli involve not only cutaneous but also proprioceptive sensations. The muscle spindles or the Golgi tendon organs, which are receptors generating the proprioceptive sensation, are slowly adapting units, while the Pacinian corpuscles, receptors that detect skin vibration, are rapidly adapting units.

Many of the participants made similar comments. The questionnaire rating clearly revealed high confidence and expectation. Their medians and quartiles confirmed that the force sensation was well perceived. Q1 indicated that the participants were aware of the direction information and found the information provided by our system to be very intuitive. Q2 confirmed that many of the participants realized the importance of force feedback in emergency navigation. The participants also commented on the quietness of the force display. They commented that the noise level of the force display would be acceptable in daily life such as in public spaces. People with visual impairments sometimes use the information provided by acoustic echoes to gain awareness of the environment. The proposed device was so quiet that this information could still be used.

It is crucial to miniaturize and lighten the force display so that it can be carried more easily. However, the amplitude of the kinesthetic stimuli, which should be large enough to be perceived, is proportional to the mass of the weight and the amplitude of acceleration. The tradeoff between the mass of the weight and strength of perception limits the amount by which the weight can be reduced. However, the size of the force display could be reduced by using other mechanisms to generate similar asymmetric oscillation such as linear actuators. We speculate that a miniaturized version of the force display could be embedded in canes for people with visual impairment. It is true that some people feel that no device should be attached to the cane, but only a relatively small amount of retraining would be needed.

7. CONCLUSION

We reported an investigation that clarifies the feasibility of using a mobile haptic direction indicator to support pedestrians with visual impairments. Results and feedback from a user study on a wayfinding system provided valuable insights. The results clearly suggest that the proposed system can be used to indicate navigation directions via kinesthetic sensation without any previous training.

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