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Assisting Visually Impaired People to Acquire Targets on a Large Wall-Mounted Display

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Abstract Large displays have become ubiquitous in our everyday lives, but these displays are designed for sighted people. This paper addresses the need for visually impaired people to access targets on large wall-mounted displays. We developed an assistive interface which exploits mid-air gesture input and haptic feedback, and examined its potential for pointing and steering tasks in human computer interaction (HCI). In two experiments, blind and blindfolded users performed target acquisition tasks using mid-air gestures and two different kinds of feedback (i.e., haptic feedback and audio feedback). Our results show that participants perform faster in Fitts' law pointing tasks using the haptic feedback interface rather than the audio feedback interface. Furthermore, a regression analysis between movement time (MT) and the index of difficulty (ID) demonstrates that the Fitts' law model and the steering law model are both effective for the evaluation of assistive interfaces for the blind. Our work and findings will serve as an initial step to assist visually impaired people to easily access required information on large public displays using haptic interfaces.

Keywords haptic I/O, auditory (non-speech) feedback, interaction style, human computer interaction, visually impaired people

1 Introduction

With significant price reductions for large LCD (liquid crystal display) panels, we have observed a dramatic increase in the use of large digital displays in public spaces. Such rapid growth in large public display systems will lead us to accommodate environments that encourage more frequent in-situ interactions that can sense and respond to users in new ways. More and more researchers are interested in demonstrating the benefits of large interactive displays[1-2].

However, in spite of the proliferation of such displays in public spaces, assistive technology for large public displays is sparse, poorly supported and lacking a sound understanding of the challenges facing visually impaired people (hereafter referred to throughout this paper as "VIPs"). The ACM (Association for Computing Machinery) code of ethics positions the use of computer resources as a fundamental ethical consideration: "In a fair society, all individuals would have equal opportunity to participate in, or benefit from, the use of computer resources regardless of race, sex, religion, age, disability, national origin, or other similar factors."①

Last year the worldwide demographic of VIPs was estimated to be as many as 285 million people (WHO, 2013)②. Clearly, VIPs cannot access the information on these displays as effortlessly as sighted people. In order to create operationally effective and emotionally fulfilling experiences for VIPs, large public display systems need to be augmented with nonvisual interface modalities (e.g., audio and/or haptic).

The integration of sound in the interface to help VIPs interact with information on a visual display has been popular. Sound is largely used to alert users and to provide feedback. Many display systems use the robust auditory channel to augment visual information for VIPs[3]. However, there are cases where the haptic channel might be a viable option for complementing visual interfaces. For example, in the public display environment, interference from background noise can significantly reduce the effectiveness of the auditory channel[4]. In such situations, devices that can convert

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①http://www.acm.org/about/code-of-ethics, July 2014.

②http://www.who.int/mediacentre/factsheets/fs282/en/, July 2014.

acoustic or visual signals into vibrotactile or electrotactile signals will provide significant benefits for VIPs.

On the other hand, the ability to point at something on the display and thereby manipulate it or perform some function is central to most modern user interfaces. Pointing and selecting interactions are ubiquitous tasks in Human Computer Interaction (HCI) and numerous new pointing and selecting interfaces continue to appear on the market. For those tasks, the well-known models for evaluation and prediction are Fitts' law and the steering law models, which are two of a few successful and reliable HCI predictive models[5-6].

Although there are studies related to Fitts' or steering tasks, we are unaware of any adaptation of these models that accounts for interaction by VIPs. In this paper, we provide a solution to assist VIPs to effectively interact with large public displays. 1) We proposed and implemented natural mid-air gesture input and a haptic feedback interface. VIPs could easily access a target on a large wall-mounted display using our system. 2) We extended the applicability of both Fitts' and steering laws in predicting and evaluating the performance of VIPs, when they interacted with a large wall-mounted display using haptic interfaces.

We believe that this paper is one of the first studies to consider the development of large display interactivity for VIPs, and it will go a long way towards granting them equal access to information that is currently available only to sighted people. Specifically, our approach was to implement a lightweight, inexpensive interface with mid-air gesture input and haptic feedback, so that VIPs can efficiently access required targets on a large display in 3D environments. Our system will make significant interaction experiences available not only to blind users but also to seniors and people with low vision. In addition, we extended Fitts' law and the steering law models to predict and evaluate performances of assistive user interfaces. In a broader sense, we expect that this study will become a stepping-stone for further researches on pervasive large interactive displays and assistive interface technologies by uniquely evaluating new interaction paradigms.

2 Related Work

We conducted a literature review on existing interaction techniques for VIPs. We focused on two main issues: 1) how VIPs initiate interactions with systems (i.e., input) and 2) how they get feedback from the systems (i.e., output) (Fig.1).

Input modalities for VIPs are classified into eight categories: 1) hand gestures[7-9], 2) upper body movement[10], 3) lower body movement[11-12], 4) environmental context[13-17], 5) braille[18-20], 6) multi-touch[21-25], 7) speech[26-29], and 8) keyboard/mouse[30-31].

Feedback from the system (i.e., output) was classified into four broad categories: 1) vibration[7,9-10,13-14], 2) speech[15,19,21-22,26,31], 3) sound[8,11-12,16,20-21,29], and 4) braille display[17-18,25,27].

To better understand the use of various displays for VIPs, we assessed past studies regarding assistive technologies for different display types. Our review revealed that assistive interactive displays ranged in size from handhelds (PDAs[14,32], palmtops[15,17], mobile phones[33-34]) to desktop sizes (laptops[9,21,30-31,35], Braille displays[20]), and to large display sizes (like tabletop displays[3]). It appears that the appropriateness of the display size correlated with the nature of the tasks involved. Large displays were often used to investigate effective target acquisition techniques for blind users. For example, the Access Overlay technique was

Output \ Input	Hand Gesture	Upper Body Movement	Lower Body Movement	Environmental Context	Braille	Multi-Touch	Speech	Keyboard/ Mouse
Vibration	Blind Hero[9], Tactile Guidance Technique[7]	Fingertip Guiding Manipulator[10]		HapticEye[13], Wayfinder[14]		Haptic Magnitude[23], Tactile-Thermal Display[24]	Multimodal Media Center[28]	Web-Based Haptic Application for the Blind[30]
Speech				Object Identification System[15]	Inexpensive Braille[19]	No Look Notes[22] Aedin[21]	Speech Input on Mobile Devices[26]	Brookes-Talk[31]
Sound	Touch Player[8]		Blind Pedestrian[11], Digital Clock Carpet[12]	Social Interaction Assistant[16]	Haptic Sudoku[20]		Touch Panel Using Stereo Camera[29]	
Braille Display				3DOD System[17]	MoBraille[18]	Tactile Windowing[25]	AVANTI Web Browser	

Fig.1. Input and output technologies for visually impaired people.

developed to help blind users to more easily select a target on a large horizontal tabletop display using touch and speech in tasks such as selecting a location on a map application[3].

We also did a literature review regarding the suitability of Fitts' law to model interactions in large display scenarios. Shoemaker *et al.*[36] conducted an evaluation of Fitts' law applicability on large displays. While some research has been conducted regarding Fitts' law tasks on large displays, little work has been done regarding blind people's interactions on large vertical displays.

The Fitts' and the steering laws could be adapted to represent pointing and steering tasks performed by VIPs on large displays, and they thus would be relevant to our purpose (e.g., representing target acquisition tasks on large wall-mounted displays).

3 Experiment System

Our experiment system has two main parts, mid-air gesture input and audio/haptic feedback. Our main consideration in the design of an assistive interface for a large wall-mounted display was to support its possible use by blind people in a public space. Public display sizes are increasing and the large displays are often positioned for viewing from a distance. Thus, the input via mid-air gestures, enabling interactions at a distance, becomes not only more viable but also more necessary, especially for VIPs. In addition, haptic and audio feedback is efficient for navigating graphical contents such as maps, diagrams, and floor plans by helping blind users build mental spatial models of the direction and the distance of graphical objects[37]. In the following subsections, we first discuss the implementation of mid-air gesture input, after which we discuss the implementation of audio/haptic feedback. Then, we explain in detail the two experiments we conducted in Section 4 and Section 5 respectively.

3.1 Mid-Air Gesture Input

We captured mid-air gestures with a Microsoft Kinect depth-sensitive camera, and used positions of the right wrist and the right hand to calculate the pointing direction vector in 3D space. The projected X (how far to the left or to the right) and Y (how far to the top or to the bottom) values of the pointing direction vector were used to control a mouse cursor on the display by a *sendMouseInput* method in the MSDN (Microsoft Developer Network Library) utility class. With this solution, users were able to control the cursor on the screen by moving the right hand in front of the camera (Fig.2).

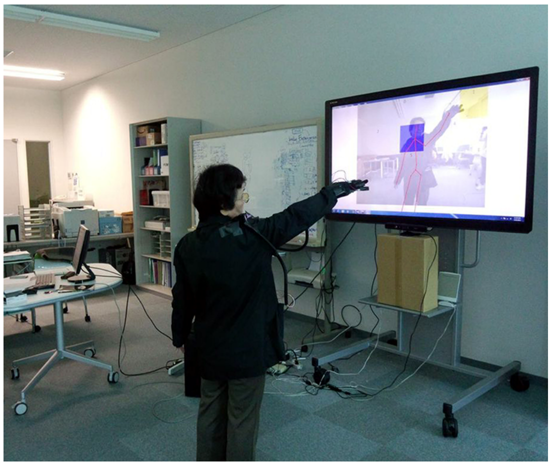

Fig.2. A visually impaired person (VIP) interacting with a large wall-mounted display using the gesture input and the haptic feedback.

3.2 Audio/Haptic Feedback

When users placed the cursor over a target, the *MouseOver* event triggered the audio or haptic feedback. For audio feedback, the system played a sound to indicate that the target had been selected. For haptic feedback, two modules were implemented, a wireless sensor network and a wearable haptic device. Fig.3 shows the wearable haptic device used in the experiment. The wireless sensor network module was built for the communication between the display and the wearable haptic device. We used XBee radios to support the

Fig.3. Jacket, glove, and wristband with a vibration control box. The box fits into the pocket of the jacket.

ZigBee protocol, which is a standard communication protocol for small, low-power digital radios for wireless personal area networks (WPAN).

The wearable haptic device consisted of eight ERM (Eccentric Rotating Mass) actuators, an Arduino Uno, an Arduino XBee shield, an amplification board, and a 9 V battery. The Arduino Uno, the Arduino XBee shield, the amplification board, and the battery were all placed together inside a small box, which could fit into a jacket pocket (Fig.3). Four independent DC-controlled vibration actuators were embedded on a wristband and a glove. The sockets of the actuators were connected to the amplification board by electric wires.

The flow of signals to generate haptic feedback was as follows. First, if a target on the display was pointed at, the display system opened a serial data communication channel to the vibration control box via XBee radios. Then, the XBee radio connected on the display system sent data (i.e., actuator number, amplitude, on and off status) wirelessly to the Arduino XBee shield on the vibration control box. After getting the data, the Arduino sent a pulse-width modulation (PWM) signal to the actuators through the amplification board. The actuators then created vibrations based on the signal.

To investigate the effectiveness of our gesture input and haptic feedback system, two experiments were conducted, the Fitts' law task in experiment 1 and the steering law task in experiment 2. The following sections describe the two experiments in detail.

4 Experiment 1: Fitts' Law Task

First we compared the effect of audio feedback and haptic feedback when VIPs tried to accomplish the task in style of Fitts' law. The original Fitts' law task was devised for interactions by sighted users. We extended it so that VIPs could access targets using audio or haptic feedback. The adaptation of the Fitts' law task is a good starting point for building a performance model for VIPs to interact with large wall-mounted displays. We examined whether the current use of Fitts' law on the visual modality of user interfaces could be extended to multimodalities with haptic and audio interfaces.

4.1 Participants

Six participants were recruited including one blind participant from a local blind association and five normal vision participants from a university. Normal sighted participants were blindfolded, so that they would rely on their haptic or hearing sensors only without seeing the display. Their ages ranged from 21 to 49 and the average was 26.5 years. All participants were right-handed males. They were paid about $10 for their participation.

4.2 Apparatus

We conducted the study using a SHARP Aquos 60 inch (142 cm W × 84 cm H) flat screen LCD hung on the stack at eye-level, and the participants performed the tasks in the standing posture. In addition, a Microsoft Kinect camera was placed at the bottom-center of the large screen to capture gestures. In the haptic condition, the participants wore the jacket and glove, which was equipped with previously mentioned haptic devices (Fig.3).

4.3 Task

Similar to the original Fitts' experiment[5], participants performed a pointing task on a pair of vertical rectangular targets by moving the right hand in the air. The mid-air arm and hand gestures were mapped to the movement of a pointing cursor on the display so that they could guide the cursor to the vertical rectangular targets (Fig.4). In addition, automatic audio or haptic feedback assisted participants to correctly point to the target, i.e., they could hear audio sounds or feel vibrations on their hands when the cursor hovered over the target. The steps for the target-pointing task were as follow.

Fig.4. Interface for Fitts' law pointing tasks in experiment 1. The two black bars are vertical rectangular targets.

1) *Move to the Starting Rectangular.* At the beginning of the task, participants raised the right hand and moved the hand toward the left target until they perceived audio or haptic feedback, which indicated access to the target. Then, the participants notified the experimenter by saying "I can feel it" or "I can hear it". The color of the target changed from black to yellow when the pointing cursor moved onto the rectangular, thus drawing it to the experimenter's notice. This left target became the starting point. Then, participants moved the hand to the right to select another vertical rectangular. The starting time was logged by the sys-

tem at the moment when the cursor exited the starting rectangular.

2) *Selecting the Target Rectangular.* Participants moved the hand to the right until audio or haptic feedback was triggered by landing on the right vertical rectangular. Then, participants stopped moving the hand. This right vertical rectangular became the target point. When the pointing cursor entered the target rectangular, the ending time was recorded by the system. Participants were asked to move the hand as quickly and accurately as possible to select the target rectangular.

3) *Repeat.* Participants repeated 1) and 2) above.

4.4 Four Feedback Conditions

The experiment had four feedback conditions, which helped VIPs select the target: 1) flashing audio feedback (hereafter called "FAF"), 2) incremental audio feedback (hereafter called "IAF"), 3) flashing haptic feedback (hereafter called "FHF"), and 4) incremental haptic feedback (hereafter called "IHF"). In the flashing feedback condition, when the pointing cursor entered the target rectangular, the audio alarm would sound or the participant's glove would vibrate. If the cursor was outside of the target, the alarm or the vibration would stop. In the incremental feedback condition, the volume of the audio alarm or the strength of the vibration would increase, as the pointing cursor got closer to the target. When the cursor entered the target rectangular, the alarm or the vibration stopped immediately. The main difference between flashing feedback and incremental feedback was that the audio or the haptic feedback in the flashing style was designed to indicate only that the cursor was on the target, whereas the audio or the haptic feedback in the incremental style was designed to be continuously activated while the cursor was moving towards the target.

4.5 Measures

We used a repeated measures within-subject design. Each participant completed all four different feedback conditions. The target widths and distances were varied. To balance out the learning effect, the order of the four feedback conditions was counterbalanced using a Latin square. Within each feedback condition, the order of the combinations for different target widths and distances was also randomized. Pointing completion time, error rate, and subjective preference were recorded during the experiment.

4.5.1 Pointing Completion Time

We measured the pointing completion time for each feedback condition. Pointing completion time was calculated as the duration from the selection of the starting rectangular to the selection of the target rectangular. Five degrees for the pointing index of difficulty (ID_p) with combinations of five widths (W) and five distances (A) to targets were investigated as Fitts' law tasks[5]:

$$ID_p = \log_2 \left(\frac{A}{W} + 1 \right).$$

The widths of the targets were set at $W = 210$, 190, 170, 150, 130 pixels (14.7 cm, 13.3 cm, 11.9 cm, 10.5 cm, 9.1 cm) respectively and the center-to-center distances or amplitudes between the two rectangulars were set at $A = 210$, 347, 510, 699, 910 pixels (14.7 cm, 24.3 cm, 35.7 cm, 48.9 cm, 63.7 cm) respectively. Thus, the values of the five ID_p calculated by the W-A combinations were 1, 1.5, 2, 2.5 and 3 respectively.

Participants repeated ten trials for each ID_p under four different feedback conditions. Therefore, the total number of repetitions afforded for data collection was:

6 participants $\times$ 4 feedback conditions $\times$
5 index of difficulty levels $\times$ 10 trials
$=$ 1 200 repetitions.

4.5.2 Error Rate

In addition to the pointing completion time, we were also interested in the error rate while selecting targets. During the experiment, if the region outside the target was selected, a mistake was recorded for error rate calculation. From time to time, participants "passed through" or "fell short of" the general region of the target. These errors were recorded when the cursor pointed beyond the target rectangular or when it stopped before reaching to the destination.

4.5.3 Subjective Preference

To evaluate ease in selecting the target and the degree of fatigue experienced, we asked the participants to answer a 7-point Likert scale questionnaire after each feedback condition (Table 1). In the questionnaire, 1 corresponds to the lowest preference and 7 to the highest preference. These questions were composed by refer-

Table 1. Questionnaires for Each Feedback Condition

Questions
1. How easy was it for you to learn the interface?
2. How easy was it for you to use the interface?
3. How tired were you after completing the work?
4. How stressful or annoyed were you after completing the work?
5. How much did you like using the system?

ring to ISO9241-400[3]. We also conducted follow-on interviews to reveal any relevant usability issues.

4.6 Procedure

Before beginning the experiments, participants were asked to complete a brief demographic survey as well as a consent form. They were then given aural instructions for the task. During the experiments, participants stood in front of the display at a distance that enabled the cursor to "reach" the rectangular targets as the users gestured in 3D space. Thus, the exact distance was different for each participant depending on his/her height, but it was generally around two meters from the display. The experimenter helped participants position themselves to face the display and so that their pointing hand would be tracked correctly. Before the actual trials, participants underwent a training period for each feedback condition, until they were confident using the feedback system. This allowed them to get a feel for the task and to familiarize themselves with the different feedback techniques for the target pointing tasks.

After the training session, the participants were asked to perform the actual trials. Every participant completed 200 combinations of target widths, target distances, and feedback conditions. The order of combinations was randomized and counterbalanced. Each participant performed the entire experiment in four sessions lasting approximately two hours. The session was divided according to the feedback conditions.

After they completed each feedback condition, participants answered the questionnaires. Finally, when participants completed all the conditions, an experimenter conducted an interview and collected qualitative data on the experience. All the experiment sessions were audio and video taped.

4.7 Results

We analyzed performance in terms of pointing completion time and error rate. A two-way ANOVA (analysis of variance) with repeated measures was used for two factors: feedback and index of difficulty. For the Fitts' law analysis, a linear regression analysis was done to ascertain whether the pointing completion time could be predicted based on the index of difficulty. For subjective preference analysis, a Friedman test was used.

4.7.1 Pointing Completion Time

There was a significant difference in the mean pointing completion time for the feedback ($F(3,15) = 3.97$, $p = 0.03$) and for the index of difficulty ($F(4,20) = 16.17$, $p < 0.001$). The overall mean completion time was 668 milliseconds for FAF, 1 080 milliseconds for IAF, 589 milliseconds for FHF, and 667 milliseconds for IHF (Fig.5).

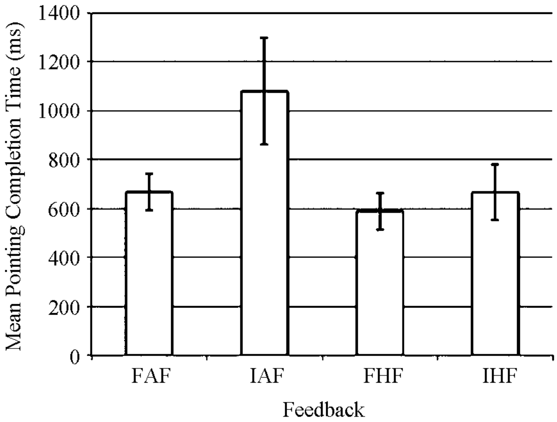

Fig.5. Mean pointing completion time for four different feedback conditions. Error bars show ±2 standard error.

We applied Fitts' law to evaluate the correlation between the pointing completion time and the index of difficulty. For all the feedback conditions, the pointing completion time (MT) and the index of difficulty (ID_p) were statistically significantly correlated. Linear regression results between the pointing completion time and the index of difficulty are summarized in Table 2. Fig.6 presents the scatter plots of the pointing completion time against the index of difficulty for the four feedback conditions.

Table 2. Summary of MT vs ID_p Regression for the Pointing Task with Four Different Feedback Conditions

Feedback	A	b	R^2
FAF	−0.141	0.405	0.938
IAF	−0.040	0.560	0.939
FHF	−0.068	0.329	0.973
IHF	0.029	0.319	0.979

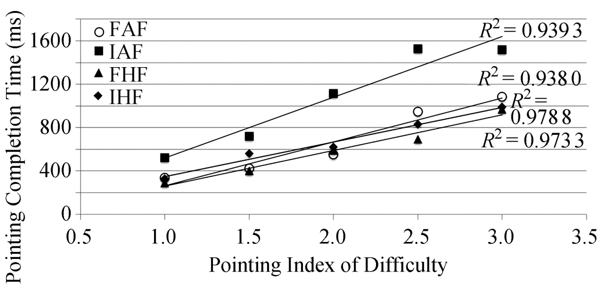

Fig.6. Linear relationship between the pointing completion time and the index of difficulty in four different feedback conditions.

[3] https://www.iso.org/obp/ui/#iso:std:iso:9241:-400:ed-1:v1:en, July 2014.

4.7.2 Error Rate

Results for error rates show a significant main effect for the index of difficulty ($F(4, 20) = 3.53$, $p = 0.03$) but no significant effect for feedback ($F(3, 15) = 0.21$, $p = 0.89$). The overall mean error rates were 10.2% for FAF, 7.7% for IAF, 10.9% for FHF, and 9.6% for IHF.

4.7.3 Subjective Preference

A Friedman test indicated that there was a statistically significant difference in perceived overall satisfaction regarding use (i.e., Question 5 in Table 1), depending on which type of feedback was used, $\chi^2(3) = 13.67$, $p = 0.003$. IHF was the most preferred, FHF was the next, and then FAF and IAF were the least preferred. We could not find any significant differences for the other questions in the questionnaire.

5 Experiment 2: Steering Law Task

Through Experiment 1, we were able to examine the effect of haptic feedback on a pointing task in which participants were required to select a vertical rectangular target. As a further study, in Experiment 2, we simulated a steering task on the large public display. The steering task requires users to drag the input device (or the pointer) a certain distance to select a target. Examples of the steering task in everyday computer use are navigating through a pull-down menu to select a sub-menu or moving a scroll bar to pan the window.

For our experiment, we chose a "tunnel steering" task, where participants had to make a hand movement trajectory from one side to the other side of the display, passing through the "tunnel"[6]. Our hypothesis was that with haptic guidance, participants would complete the task as accurately and fast as they did with audio guidance.

5.1 Participants

The same six participants from Experiment 1 took part in Experiment 2. They were paid an extra $10 for their participation.

5.2 Apparatus

We used the same wall-mounted SHARP Aquos 60 inch flat display and the Kinect motion-sensing camera as those in Experiment 1. To support the haptic warning feedback (hereafter "HWF"), we attached four vibration actuators to the glove, which participants wore on the right hand. Those actuators were carefully sewn onto a thin-fabric glove to ensure the stability during hand movements. One vibration actuator was attached to the back of the hand, one to the palm of the hand, one on the index finger, and one on the little finger. These indicated cardinal directions of movement: up, down, left and right respectively. For the audio warning feedback (hereafter "AWF"), a sound was used as an alarm when the pointing cursor entered the warning zone.

5.3 Task

There was a virtual horizontal tunnel on the screen (Fig.7). Participants needed to pass their hands along the tunnel from left to right, while staying inside the tunnel. The mid-air arm and hand gesture was mapped to the movement of a pointing cursor on the display so that participants could control the cursor.

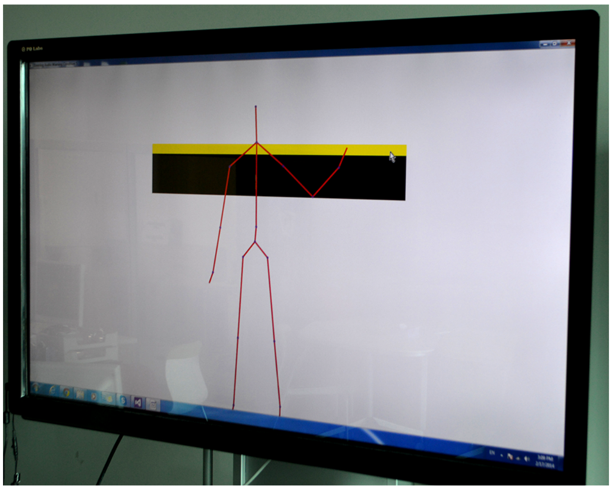

Fig.7. Interface for the steering law task in experiment 2. The black bar is a trajectory tunnel and the yellow bar shows a warning zone.

When the pointing cursor approached the top border of the tunnel, the participants would hear a warning sound under the AWF condition, or feel a warning vibration on the HWF condition. Then, they adjusted themselves to lower the hand to avoid touching the top border. Also, the color of the top border-warning zone changed from black to yellow to alert the experimenter (although the VIPs participants could not see this color change). In the same way, when the pointing cursor approached the bottom border of the tunnel, the participants would hear another warning sound, or feel the warning vibration. Then, they needed to raise their hand to avoid touching or crossing the bottom border of the tunnel.

If the hand crossed the top or the bottom border, the game-over sound would play and the participants would restart the steering task from the beginning. Otherwise, once they passed through the tunnel successfully, they could hear the game-ending sound. Then, we asked the participants to move the hand back to the starting position on the left side of the tunnel and steer through the tunnel again. Participants were asked to complete the task as quickly and accurately as possible.

We varied the combinations of tunnel length and width, and the participants repeated the steering tasks several times for each combination.

5.4 Measures

The steering completion time, error rate, and subjective preferences were recorded during the experiment.

5.4.1 Steering Completion Time

We measured the steering completion time for five degrees of the steering index of difficulty (ID_s) with the combinations of five tunnel widths (W) and five tunnel lengths (A). ID_s was defined from the original steering law[6]:

$$ID_s = \frac{A}{W}.$$

Steering completion time was calculated as the duration of steering from the moment the pointing cursor crossed the starting point on the left side of the tunnel, to the moment the cursor crossed the end point on the right side of the tunnel. The time was automatically logged by the system based on the cursor's positions.

Five widths for the tunnel were set at $W = 250$, 200, 180, 160, 150 pixels (17.5 cm, 14 cm, 12.6 cm, 11.2 cm, 10.5 cm) respectively and five lengths for the tunnel were set at $A = 500$, 600, 720, 800, 900 pixels (35 cm, 42 cm, 50.4 cm, 56 cm, 63 cm) respectively. Thus, the values of five ID_s calculated by the W-A combinations were 2, 3, 4, 5 and 6 respectively. Every participant performed five combinations of ID_s, with AWF and HWF. They repeated each combination ten times. Therefore, the total number of repetitions afforded for data collection was:

6 participants × 2 feedback conditions ×
5 index of difficulty levels × 10 trials
= 600 repetitions.

5.4.2 Error Rate

We also measured the error rate on the steering task. During the experiment, if the participants exited the tunnel region by crossing over either the top borderline or the bottom borderline, an error was recorded. When an error occurred, participants had to restart the task from the starting position.

5.4.3 Subjective Preference

We asked the participants to answer a 7-point Likert scale questionnaire after completing the task on each condition, as shown in Table 1. We also conducted interviews to discover any useful insights and usability issues.

5.5 Procedure

At the beginning of the experiment, participants were given aural instructions about the task. Following this, the participants underwent a training period allowing them to familiarize themselves with the task and the system. During the 10-minute training session, the participants were permitted to practice steering tunnels and they were allowed to ask for clarification. To minimize recognition errors by the Kinect sensor, participants were asked to point their right hand at the display while stretching the fingers out, facing the palm downward the earth, and standing about two meters from the display. The experimenter assisted participants so that they might stand in the right position and control a cursor with mid-air gestures.

The order of experiment conditions for different feedback types and the index of difficulty were randomized and counterbalanced using a Latin square. Each participant performed the entire experiment in one session lasting approximately one hour. There were short breaks between each feedback condition. After all the trials, the participants completed questionnaires. Experimenters also interviewed the participants in order to collect qualitative data on their experiences during the experiment.

5.6 Results

We analyzed performance in terms of steering completion time and error rate. All results were analyzed using a within-subjects analysis of variance (ANOVA), evaluated at an alpha level of 0.05. A linear regression analysis was performed to ascertain whether the steering completion time could be predicted based on the index of difficulty. For subjective preference analysis, a Friedman test was used.

5.6.1 Steering Completion Time

Results for the steering completion time showed significant main effect for the index of difficulty ($F(4, 20) = 5.42$, $p = 0.004$) but no significant effect for the feedback ($F(1, 5) = 0.40$, $p = 0.55$). The overall mean steering completion time was 1.2 seconds for AWF, 0.95 seconds for HWF.

We applied the steering law to evaluate the correlation between the steering completion time and the index of difficulty. For all the feedback conditions, the steering completion time (MT) and the index of difficulty (ID_s) were statistically significantly correlated. Linear regression results between the steering completion time and the index of difficulty are summarized in Table 3. Fig.8 presents the scatter plots of the steering completion time against the index of difficulty for two feedback conditions.

Table 3. Summary of MT vs ID_s Regression for the Steering Task with Two Different Feedbacks

Feedback	a	b	R^2
AWF	0.306	0.223	0.922
HWF	0.132	0.204	0.978

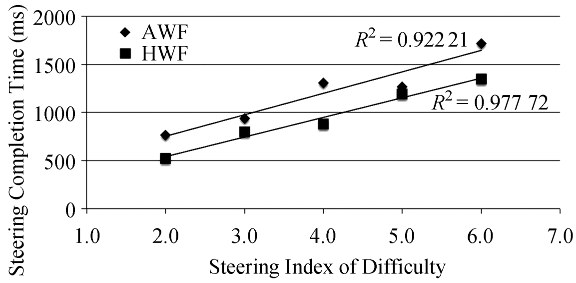

Fig.8. Linear relationship between the steering completion time and the index of difficulty for two different feedbacks.

5.6.2 Error Rate

Results for error rates showed no significant main effect, for either the feedback ($F(1,5) = 0.16$, $p = 0.71$) or the index of difficulty ($F(4,20) = 1.68$, $p = 0.19$). The overall mean error rates were 2.1% for AWF and 2.7% for HWF.

5.6.3 Subjective Preference

A Friedman test indicated that there was a statistically significant difference in perceived overall satisfaction (i.e., Question 5 in Table 1), depending on which type of feedback condition was used, $\chi^2(1) = 4.0$, $p = 0.046$. Participants preferred haptic warning to audio warning for the steering task. We could not find any significant differences for the other questions in the questionnaire.

6 Discussion

One of our goals in this study was to investigate whether haptic feedback could be effective in helping blind users acquire a required target on a large wall-mounted display. We adopted two fundamental performance models in HCI, Fitts' law and the steering law, to evaluate the devised assistive interface. In Experiment 1, the performances of two haptic feedback modes (i.e., flashing mode and incremental mode) were overall successful in pointing tasks. When feedback occurred only upon the contact with a target in the flashing mode, participants were able to complete the pointing task more quickly with haptic feedback than with audio feedback. On the other hand, when the strength of feedback was set to continuously increase as the hand approached the target in the incremental mode, participants were able to complete the pointing task with haptic feedback just as quickly as with audio feedback.

Generally, in the incremental feedback mode, participants had fewer errors than in the flashing feedback mode. This showed that there was a trade-off between the accuracy and the speed, i.e., faster completion produced more errors. From the interview with participants after the experiment, we were able to infer the reason for this observation: as vibration occurred continuously, the participants' judgment regarding the most intense vibration varied, and they reacted tentatively and slowly to the approach to the target. All participants except one said that it was much easier to distinguish and react to simple on/off vibration at the moment of arrival at the target.

For the steering task in Experiment 2, we found that there was no significant difference between haptic feedback and audio feedback in respect of completion time or error rate. This result implied that participants could complete the steering task with haptic feedback just as accurately and quickly as with audio feedback. Furthermore, all participants mentioned at the post-experiment interview that they could do the work better with haptic warning than with audio warning. Thus, it can be argued when audio feedback is not the best choice such as in a noisy environment, haptic feedback will be a good alternative to support interaction with a large display.

In this study, we found that Fitts' law is effective for predicting and evaluating the performance of VIPs in pointing or steering a target on a large wall-mounted display with haptic or audio feedback. Fitts' law has been applied mainly for ballistic aiming movement, where users can plan the movement at the start. According to the pioneering work of Woodworth[38], the goal-directed aiming movement has two phases, a ballistic movement phase, which covers most of the distance, followed by a deceleration movement phase to the final goal. Previous work found that visual feedback mainly controlled the deceleration phase in aiming movements[39]. Likewise, in Fitts' law, as the index of difficulty increases, visual feedback becomes more important in the deceleration stage. Through our experiments, we examined the use of Fitts' law for environments where participants could not see where the target was so that they could not plan the movement prior to the start of the movement. The results showed the potential for applying Fitts' law even for non-visual interfaces such as haptic or audio interfaces. This finding can help user interface designers when designing assistive user interfaces for VIPs as we propose in our study.

The ability to point a target on an interface is the first step for further manipulation and it is central to most modern graphical user interfaces. Despite the considerable body of existing literature on pointing and selecting, the present study is, to the best of our knowledge, among the first of its kind in that we are concerned with VIPs and their use of large vertical displays. Specifically, we present natural gesture input aided by haptic feedback. As a further study, we are investigating the theoretical rationale regarding how Fitts' law could also be applicable to predicting and evaluating a performance model for VIP-computer interaction on non-visual interfaces.

The prototype in this study required VIPs to wear extra equipment on their bodies. It may be desirable to eliminate this requirement. Since the mobile phone is becoming a popular commodity for VIPs, one promising way of getting haptic feedback from a large public display is through mobile phones. We are developing the prototype of mobile phone haptic devices as a next step.

There is a body of research pertaining to eyes-free target acquisition interaction[40-44]. CAVIAR[40] supports acquiring objects in the peripersonal space. In CAVIAR, a wristband with its vibrotactile actuators generates continuous stimuli for guiding the user's hand. The wristband is directed via Bluetooth from a mobile phone, which recognizes and tracks the hand and objects using computer vision. Morelli *et al.*[41-42] presented haptic feedback to point out the location of a virtual object in tactile-proprioceptive displays and evaluated multilinear target-scanning in a plane in front of the user. Their vibrotactor used pulse delay and frequency to provide directional vibrotactile feedback. Virtual shelves[43-44] were for selecting nonvisual objects by positioning a Wiimote within a virtual circular hemisphere defined in front of the user. The major distinctions between these existing eyes-free search methods and our work are as follows. 1) We focus on interactions with the large wall-mounted display rather than on interactions with assistive mobile devices. Accordingly, the use of our approach to blind manipulation of a large vertical display and, at a higher level, the application of finding strategies could be included in general search algorithms for use by VIPs. 2) Instead of tracking an active LED marker[41-42,44] or using an accelerometer and a gyroscope to sense the position and orientation[43], our system can trace barehanded movements in absolute coordinates, providing more natural interaction experiences.

This study has shown an approach to the design and development of an assistive interface for VIPs to perform fundamental HCI tasks in mid-air interaction environments. Future work includes conducting an additional experiment with more blind participants to fully validate the value of our findings.

7 Conclusions

While the rapid growth of large interactive display systems in our everyday lives enables sighted people to spontaneously and naturally walk-up-and-use public information, those technologies remain largely inaccessible to blind people. In this study, we explored the feasibility of mid-air gesture input and haptic feedback to help blind people access targets on large displays more easily. The performance results of our studies attest to the potential for blind users to access targets on interactive large displays. In addition, we studied the applicability of Fitts' law and the steering law for the evaluation of assistive user interfaces. Our results show that both Fitts' law and the steering law are valid for predicting eyes-free target acquisition time on both haptic and audio feedback interfaces. Our work and findings will serve as a significant initial step towards granting visually impaired people equal access to information on large public displays.

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References

[1] Hinrichs U, Carpendale S, Valkanova N, Kuikkaniemi K, Jacucci G, Vande M A. Interactive public displays. *IEEE Computer Graphics and Applications*, 2013, 33(2): 25-27.

[2] Rashid U, Nacenta M A, Quigley A. Factors influencing visual attention switch in multi-display user interfaces: A survey. In *Proc. the 1st Int. Symp. Pervasive Displays*, June, 2012, pp.1-6.

[3] Kane S, Morris M, Perkins A, Wigdor D, Ladner R E, Wobbrock J O. Access overlays: Improving non-visual access to large touch screens for blind users. In *Proc. the 24th ACM Symp. User Interface Software and Technology* (*UIST*), October 2011, pp.273-282.

[4] Hoggan E, Crossan A, Brewster S, Kaaresoja T. Audio or tactile feedback: Which modality when? In *Proc. the 27th SIGCHI Conf. Human Factors in Computing Systems* (*CHI*), April 2009, pp.2253-2256.

[5] Fitts P M. The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology*, 1954, 47: 381-391.

[6] Accot J, Zhai S. Beyond Fitts' law: Models for trajectory-based HCI tasks. In *Proc. the 15th SIGCHI Conf. Human Factors in Computing Systems* (*CHI*), March 1997, pp.295-302.

[7] Lehtinen V, Oulasvirta A, Salovaara A, Nurmi P. Dynamic tactile guidance for visual search tasks. In *Proc. the 25th ACM Symp. User Interface Software and Technology* (*UIST*), October 2012, pp.445-452.

[8] Pirhonen A, Brewster S, Holguin C. Gestural and audio metaphors as a means of control for mobile devices. In *Proc.*

the 20th SIGCHI Conf. Human Factors in Computing Systems (*CHI*), April 2002, pp.291-298.

[9] Yuan B, Folmer E. Blind hero: Enabling guitar hero for the visually impaired. In *Proc. the 10th ACM Conf. Computers and Accessibility* (*ASSETS*), October 2008, pp.169-176.

[10] Nomura Y, Yagi Y, Sugiura T, Matsui H, Kato N. A fingertip guiding manipulator for mental image creation of multi-stroke drawings. *Microsyst. Technol.*, 2007, 13(8): 905-910.

[11] Bousbia-Salah M, Fezari M, Hamdi R. A navigation system for blind pedestrians. In *Proc. the 16th IFAC World Congress*, July 2005, pp.1401-1405.

[12] Sánchez J, Sáenz M, Ripoll M. Usability of a multimodal videogame to improve navigation skills for blind children. In *Proc. the 11th ACM SIGACCESS Conf. Computers and Accessibility* (*ASSETS*), October 2009, pp.35-42.

[13] Tsetserukou D. FlexTorque, FlexTensor, and HapticEye: Exoskeleton haptic interfaces for augmented interaction. In *Proc. the 2nd Int. Augmented Human Conf.* (*AH*), March 2011, Article No. 33.

[14] Heuten W, Henze N, Boll S, Pielot M. Tactile wayfinder: A non-visual support system for wayfinding. In *Proc. the 5th Nordic Conf. Computer-Human Interaction: Building Bridges* (*NordiCHI*), October 2008, pp.172-181.

[15] Hub A, Diepstraten J, Ertl T. Design and development of an indoor navigation and object identification system for the blind. In *Proc. the 6th ACM SIGACCESS Conf. Computers and Accessibility* (*ASSETS*), October 2004, pp.147-152.

[16] Krishna S, Colbry D, Black J, Balasubramanian V, Panchanathan S. A systematic requirements analysis and development of an assistive device to enhance the social interaction of people who are blind or visually. In *Proc. Workshop on Computer Vision Applications for the Visually Impaired* (*CVAVI 08*), Oct. 2008.

[17] Zeng L, Prescher D, Weber G. Exploration and avoidance of surrounding obstacles for the visually impaired. In *Proc. the 14th ACM SIGACCESS Conf. Computers and Accessibility* (*ASSETS*), October 2012, pp.111-118.

[18] Azenkot S, Fortuna E. Improving public transit usability for blind and deaf-blind people by connecting a braille display to a smartphone. In *Proc. the 12th ACM SIGACCESS Conf. Computers and Accessibility* (*ASSETS*), October 2010, pp.317-318.

[19] Southern C, Clawson J, Frey B, Abowd G, Romero M. An evaluation of BrailleTouch: Mobile touchscreen text entry for the visually impaired. In *Proc. the 14th Int. Conf. Human-Computer Interaction with Mobile Devices and Services* (*MobileHCI*), September 2012, pp.317-326.

[20] Gutschmidt R, Schiewe M, Zinke F, Jürgensen H. Haptic emulation of games: Haptic Sudoku for the blind. In *Proc. the 3rd Int. Conf. Pervasive Technologies Related to Assistive Environments* (*PETRA*), June 2010, Article No. 2.

[21] Ferati M, Mannheimer S, Bolchini D. Usability evaluation of acoustic interfaces for the blind. In *Proc. the 29th ACM Int. Conf. Design of Communication* (*SIGDOC*), October 2011, pp.9-16.

[22] Bonner M N, Brudvik J T, Abowd G D, Edwards W K. No-look notes: Accessible eyes-free multi-touch text entry. In *Proc. the 8th Int. Conf. Pervasive Computing* (*Pervasive*), May 2010, pp.409-426.

[23] Douglas S A, Willson S. Haptic comparison of size (relative magnitude) in blind and sighted people. In *Proc. the 9th ACM SIGACCESS Conf. Computers and Accessibility* (*ASSETS*), October 2007, pp.83-90.

[24] Hribar V, Pawluk D. A tactile-thermal display for haptic exploration of virtual paintings. In *Proc. the 13th ACM SIGACCESS Conf. Computers and Accessibility* (*ASSETS*), October 2011, pp.221-222.

[25] Prescher D, Weber G, Spindler M. A tactile windowing system for blind users. In *Proc. the 12th ACM SIGACCESS Conf. Computers and Accessibility* (*ASSETS*), October 2010, pp.91-98.

[26] Azenkot S, Lee N B. Exploring the use of speech input by blind people on mobile devices. In *Proc. the 15th ACM SIGACCESS Conf. Computers and Accessibility* (*ASSETS*), October 2013, Article No. 11.

[27] Stephanidis C, Paramythis A, Karagiannidis C, Savidis A. Supporting interface adaptation: The AVANTI web-browser. In *Proc. the 3rd ERCIM Workshop on User Interfaces for All* (*UI4ALL*), Nov. 1997, pp.3-4.

[28] Turunen M, Hakulinen J, Melto A *et al.* Speech-based and multimodal media center for different user groups. In *Proc. the 10th Annual Conf. Int. Speech Communication Association* (*INTERSPEECH*), September 2009, pp.1439-1442.

[29] Yamashita A, Kuno S, Kaneko T. Assisting system of visually impaired in touch panel operation using stereo camera. In *Proc. the 18th IEEE Int. Conf. Image Processing* (*ICIP*), September 2011, pp.985-988.

[30] Yu W, Kangas K, Brewster S. Web-based haptic applications for blind people to create virtual graphs. In *Proc. the 11th IEEE Symp. Haptic Interfaces for Virtual Environment and Teleoperator Systems* (*HAPTICS*), March 2003, pp.318-325.

[31] Zajicek M, Powell C, Reeves C. A web navigation tool for the blind. In *Proc. the 3rd ACM Conf. Computers and Accessibility* (*ASSETS*), April 1998, pp.204-206.

[32] Kim C G, Song B S. Design of a wearable walking-guide system for the blind. In *Proc. the 1st Int. Convention on Rehabilitation Engineering & Assistive Technology* (*i-CREATe*), April 2007, pp.118-122.

[33] Azenkot S, Prasain S, Borning A, Fortuna E, Ladner R E, Wobbrock J O. Enhancing independence and safety for blind and deaf-blind public transit riders. In *Proc. the 29th SIGCHI Conf. Human Factors in Computing Systems* (*CHI*), May 2011, pp.3247-3256.

[34] Jeon M, Nazneen N, Akanser O, Ayala-Acevedo A, Walker B. Listen2dRoom: Helping blind individuals understand room layouts. In *Proc. the 30th SIGCHI Conf. Human Factors in Computing Systems — Extended Abstract* (*CHI EA*), May 2012, pp.1577-1582.

[35] Brewster S, Brown L. Tactons: Structured tactile messages for non-visual information display. In *Proc. the 5th Conf. Australasian User Interface* (*AUIC*), Jan. 2004, pp.18-22.

[36] Shoemaker G, Tsukitani T, Kitamura Y, Booth K S. Two-part models capture the impact of gain on pointing performance. *ACM TOCHI*, 2012, 19(4): Article No. 28.

[37] Goncu C, Marriott K. GraVVITAS: Generic multi-touch presentation of accessible graphics. In *Proc. the 13th Int. Conf. Human-Computer Interaction* (*INTERACT*), September 2011, pp.30-48.

[38] Woodworth R S. The accuracy of voluntary movement. *Psychological Monographs*, 1970, 3(3): 1-114.

[39] Carlton L G. Control processes in the production of discrete aiming responses. *Journal of Human Movement Studies*, 1979, 5: 115-124.

[40] Bahram S, Chakraborty A, Amant R S. CAVIAR: A vibrotactile device for accessible reaching. In *Proc. ACM Int. Conf. Intelligent User Interfaces* (*IUI*), February 2012, pp.245-248.

[41] Fiannaca A, Morelli T, Folmer E. Haptic target acquisition to enable spatial gestures in nonvisual displays. In *Proc. the 39th Graphics Interface* (*GI*), May 2013, pp.213-219.

[42] Folmer E, Morelli T. Spatial gestures using a tactile-proprioceptive display. In *Proc. the 6th Int. Conf. Tangible, Embedded and Embodied Interaction* (*TEI*), February 2012, pp.139-142.

[43] Li F C Y, Dearman D, Truong K N. Leveraging proprioception to make mobile phones more accessible to users with visual impairments. In *Proc. the 12th ACM SIGACCESS Conf. Computers and Accessibility* (*ASSETS*), October 2010, pp.187-194.

[44] Li F C Y, Dearman D, Truong K N. Virtual shelves: Interactions with orientation aware devices. In *Proc. the 22nd ACM Symp. User Interface Software and Technology* (*UIST*), October 2009, pp.125-128.

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