Int. J. Human-Computer Studies 86 (2016) 109–120

Contents lists available at ScienceDirect

Int. J. Human-Computer Studies

journal homepage: www.elsevier.com/locate/ijhcs

Assisting people with visual impairments in aiming at a target on a large wall-mounted display ☆

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ARTICLE INFO

Article history:
Received 29 January 2015
Received in revised form
11 August 2015
Accepted 8 October 2015
Communicated by Stephen Laycock
Available online 23 October 2015

Keywords:
Assistive technology
Blind
Visual impairment
Large vertical display
Haptic
Air gesture

ABSTRACT

Large interactive displays have become ubiquitous in our everyday lives, but these displays are designed for the needs of sighted people. In this paper, we specifically address assisting people with visual impairments to aim at a target on a large wall-mounted display. We introduce a novel haptic device, which explores the use of vibrotactile feedback in blind user search strategies on a large wall-mounted display. Using mid-air gestures aided by vibrotactile feedback, we compared three target-aiming techniques: Random (baseline) and two novel techniques – Cruciform and Radial. The results of our two experiments show that visually impaired participants can find a target significantly faster with the Cruciform and Radial techniques than with the Random technique. In addition, they can retrieve information on a large display about twice as fast by augmenting speech feedback with haptic feedback in using the Radial technique. Although a large number of studies have been done on assistive interfaces for people who have visual impairments, very few studies have been done on large vertical display applications for them. In a broader sense, this work will be a stepping-stone for further research on interactive large public display technologies for users who are visually impaired.

1. Introduction

With considerable progress in display technologies and interaction techniques, we are observing increasing affordability and availability of large interactive displays in our everyday lives. The rapid growth of such large public displays allows us to access a wide range of information in diverse places and the contents are now much more interactive. However, the proliferation of large interactive displays also creates great challenges for people with visual impairments who require equal access to information on displays that are predominately visual. Accommodating the special needs of people with visual impairments is not only socially valuable but also produces more effective and widely useful interfaces for everyone (ACM Code of Ethics and Professional Conduct, 2015).

Assistive technology research has come a long way and has yielded many effective interfaces. Nevertheless, assistive technology for *large vertical displays* is still sparse and poorly supported in part due to the lack of a good understanding of the challenges faced by *people with visual impairments*. This paper investigates how to facilitate a target-aiming task on a large wall-mounted display by people with visual impairments. The ability to correctly select a target on an interface is the first step toward further manipulation and it is fundamental in most modern graphical user interfaces. Specifically, we present three target-aiming techniques – Random, Cruciform, and Radial – using natural gesture input aided by directional vibrotactile feedback. In all three techniques, our users with visual impairments point their hands at the large wall-mounted display, and this mid-air, non-contact gesture is tracked by a computer vision system and mapped to a cursor position onto the screen like a mouse using ray-casting (Fig. 1). To determine the best search direction, vibrotactile stimuli are delivered by means of a mobile phone held in the pointing hand. The three target-aiming techniques differ in the geometric path along which the search is performed and the way vibrotactile stimulus is provided for guidance. In Experiment 1, we evaluated three target-aiming strategies with eleven visually impaired participants to find out which search strategy was the best. In Experiment 2, we compared haptic feedback efficiency and speech feedback efficiency, which were used in our target-aiming

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☆ This paper has been recommended for acceptance by Henrik Iskov Christensen.

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http://dx.doi.org/10.1016/j.ijhcs.2015.10.002
1071-5819/

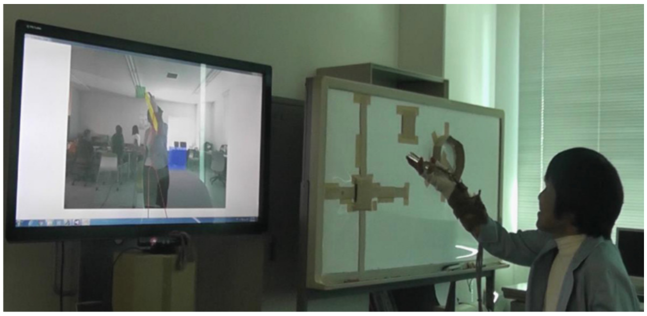

Fig. 1. A user with visual impairments aims towards a target on the display using the Radial technique.

strategies. The task was finding a bus schedule available on a large vertical digital display. According to the Royal National Institute of Blind People report (Pavey et al., 2009), the information on bus and train station boards is generally inaccessible for people with visual impairments, and this greatly affects their day-to-day mobility and freedom outside the home. We studied whether our novel vibrotactile target-aiming system enables participants with visual impairments to access train schedule information on a large vertical display, so providing equal access to the information. Both experiments were conducted with people with visual impairments. The present study is, to the best of our knowledge, among very few of its kind in that it is concerned with the use of a large vertical display by people with visual impairments. Our lightweight, low-cost interface allows people with visual impairments to dynamically access targets on a large vertical display in a 3D environment. The findings of our two experiments will serve as an initial step towards enhancing the interactivity of large vertical displays for people with visual impairments, with an ultimate goal of granting them equal access to public displays that are currently accessible almost exclusively to sighted people.

2. Related work

This section reports the results of a literature survey of existing assistive technologies for people with visual impairments in order to identify cases relevant to large vertical displays. Its emphasis was on devices, the types of sensory feedback, and eyes-free target selection.

2.1. Assistive device/display types

Interactive devices for assisting people with visual impairments have various form factors. Small, portable ones include wearable widgets such as a vibrotactile glove (Krishna et al., 2010) and a wearable camera (Jeon et al., 2012; Shilkrot et al., 2015); handhelds such as a pen (Evreinova et al., 2013), a PDA (Ghiani et al., 2009; Sanchez et al., 2008), a smartphone (Azenkot et al., 2011, 2013; Southern et al., 2012), force disk (Amemiya and Sugiyama, 2009) as well as Wii Remote (Morelli et al., 2010); and an electronic white cane (Astler et al., 2011; Fernandes et al., 2009). Large displays like tabletops (Kane et al., 2011, 2013b; Manshad et al., 2013) have also been used.

The form factor appears to be correlated to the nature of the task involved. For example, FingerReader (Shilkrot et al., 2015) was implemented in a small finger-worn device to support the blind in reading printed text by scanning with the finger and hearing the scanned words through synthesized speech. This system utilized computer vision algorithms, along with audio cues (e.g., a simple utterance of “up” or “down”) and tactile cues (e.g., a gradually increasing vibration to indicate vertical deviation from the line) to indicate in which direction the finger should move. StickGrip (Evreinova et al., 2013) provided a motorized pen grip, which was sliding up and down in relation to the distance from the pen tip to the virtual surface being explored, so that a user could explore complex topographic and mathematical onscreen images or virtual surfaces. In their experiment, blindfolded subjects relied mainly on the proprioception and kinesthetic sense in the fingers.

To assist blind users with photo taking and photo sharing, smartphones have become very popular devices. EasySnap (White et al., 2010) and Accessible Photo Album (Harada et al., 2013) were developed for the Apple iPhone by employing iOS’s VoiceOver screen reading functionality. PortraitFramer (Jayant et al., 2011) on Android phones explored the usefulness of haptic and audio cues for proper people positioning in group photos. The portability of the embedded camera and smartphone made them useful as mainstream crowdsourcing devices for collecting information regarding everyday visual challenges faced by people with visual impairments (Bigham et al., 2010; Brady et al., 2013). In addition, BrailleTouch (Southern et al., 2012) implemented a six-key chorded Braille soft keyboard on iPod touchscreen with keyclick audio feedback to support eyes-free text entry. While braille has been often used in today’s note-taking systems, the standard Perkins Brailler encodes only 63 (2^6-1) characters on a 3×2 binary matrix, with the dots numbered one through six in column-major order, and its use for graphical content is a challenge.

On the other hand, large tabletop displays were used for collaborative learning or target acquisition by people with visual impairments. For example, Trackable Interactive Multimodal Manipulatives (TIMMs) provided multimodal feedback (e.g., speech, sound/music, vibration/force feedback) to enable collaborative learning between sighted and blind students (Manshad et al., 2013). Access Overlays (Kane et al., 2011) and Touchplates (Kane et al., 2013b) supported easy target selection on a tabletop, e.g., selecting a location on a map, by providing speech or tactile feedback.

2.2. Sensory feedback types

In most of the assistive technologies we reviewed, the auditory and/or haptic channels are the de-facto channels for providing sensory feedback. Audio feedback, such as text-to-speech, is quite effective for communication between systems and people with visual impairments. For example, Blobby (Nicolau et al., 2009) used familiar and easily understandable speech, behaving like a blind companion, to help people with visual impairments navigate through unfamiliar places. Auditory icons, or earcons, are also useful. DigiTaps (Azenkot et al., 2013) presented an eyes-free number entry method for touchscreen devices, which required minimal audio feedback. It provided haptic and optional audio feedback, vibrating and speaking each digit when a gesture was entered on the screen. Their experimental results showed DigiTaps with audio feedback was slower but more accurate than with no audio feedback after each input.

Audio feedback has often been augmented with haptic feedback. It was shown that people with visual impairments could perceive an audio-based representation of a bar graph using a pointing device if provided with adequate tactile feedback (Wall and Brewster, 2006). Haptic feedback presented by a tactile array can enable people with visual impairments to perceive graphical information and form a mental model for visual imagery. For example, GraVVITAS demonstrated that the combination of a touch sensitive tablet and a data glove with vibrating actuators could be an effective technique for representing tactile graphics to users with visual impairments (Goncu and Marriott, 2011). Ghiani et al. (2009) also showed that vibrotactile feedback enhancement for vocal comment in mobile guides was particularly useful to provide frequent unobtrusive indications such as the proximity of an obstacle or the angular discrepancy from the right orientation.

2.3. *Eyes-free gestural target acquisition*

There has been a body of research pertaining to eyes-free target acquisition interaction (Bahram et al., 2012; Chan et al., 2013; Cockburn et al., 2011; Fiannaca et al., 2013; Folmer and Morelli, 2012; Li et al., 2009, 2010; Manduchi and Coughlan, 2014). FingerPad (Chan et al., 2013) permitted eyes-free interaction through the pinch gesture. It used a nail-mounted magnetic tracking device and mimicked natural haptic feedback on a touchpad. It mainly supported small-scale selection such as the selection of tiny targets (side length of 10 mm, 5 mm, and 0.6 mm) at a reading distance (40 cm), which is, in many respects, unlike eyes-free aiming at a target on a large wall-mounted display. CAVIAR (Bahram et al., 2012) supported acquiring objects in the peri-personal space. In CAVIAR, a wristband with vibrotactile actuators generated continuous stimuli to guide the user's hand. The wristband was directed via Bluetooth from a mobile phone that recognized and tracked the hand and objects using computer vision. Air pointing (Cockburn et al., 2011) enabled eyes-free interactions, where users relied on proprioception and kinesthesia rather than vision. They gradually reduced the amount of visual feedback until there was none. The effect of different feedback techniques on accuracy and learnability was suggested as the extension of their study. Fiannaca et al. (2013) and Folmer and Morelli (2012) 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 (Li et al., 2009, 2010) was for selecting imaginary objects by positioning a Wiimote within a virtual circular hemisphere defined in front of the user. On the other hand, the Last Meter (Manduchi and Coughlan, 2014) investigated the effects of frame rate and camera field of view on the ability of users with visual impairments to search for visual targets. GIST offered spatial perception using a wearable depth-sensing camera and synthetic speech feedback (Khambadkar and Folmer, 2013). GIST provided different kinds of spatial information depending on the user's hand gesture and arm orientation. However, the guiding mechanism for correct target direction by sensory feedback is absent from GIST. Aforementioned related work using different types of haptic modulation to indicate the direction to the target are compared in detail with our target-aiming techniques in following sections.

2.4. *Distinction from previous work*

The unique challenges that we try to solve in this study and the major distinctions between existing eyes-free search methods and our work are as follows.

- In general, there are a number of differences between interactions on horizontal displays and vertical displays, as pointed out in Rogers and Lindley (2004). Unlike the interaction with a horizontal display where blind users typically use the edges or corners of the display to organize and browse items (Kane et al., 2008, 2011), it is not easy for people with visual impairments to touch the screen or slide their hand across the edges of a vertical display because large vertical displays are usually hung at an unreachable height and distance from the viewer. To our knowledge, this study is the first to show the use of vibrotactile feedback for mid-air gesture, which enables people with visual impairments to interact with a large vertical display at a distance.
- Although some studies suggested that audio or haptic feedback can augment spatial search on a large display by guiding the hand actively toward the target, they were designed to support either sighted users on a vertical display (Lehtinen et al., 2012) or blind users on a horizontal display using touch input (Kane et al., 2011). However, little study has been done for *blind* users to access information on large *vertical* displays. When developing assistive technology for people with visual impairments, it is very important to test it with the target demographic, i.e., people with visual impairments in this case; numerous studies have found significant differences between populations with regards to haptic perception and spatial memory (Postma et al., 2007). From that perspective, our study reports two such experiments with participants with visual impairments for target search tasks on a large vertical display.
- We focus on interactions with large wall-mounted displays by people with visual impairments, rather than on interactions with assistive mobile devices like SpaceSense (Yatani et al., 2012) or Virtual shelves (Li et al., 2010). Therefore, the use of our approach for blind manipulation on a large vertical display and, more specifically, the systematic search patterns with haptic guidance that we have developed can be regarded as general haptic search strategies for use by people with visual impairments.
- We render unique vibrotactile flows using a new haptic rendering method. Our use of a mobile device augmented with commercially-available actuators without any vibration damping mechanism can be quite practical, and takes an approach that is different from previous designs such as the wristband in CAVIAR (Bahram et al., 2012), Sony PlayStation Move controllers used in (Fiannaca et al., 2013; Folmer and Morelli, 2012), Wii Motion Plus in Li et al. (2009, 2010), ALPS force reactor in Traxion (Rekimoto, 2013), and the magnetic plate in FingerPad (Chan et al., 2013). Our device provides directional sensations similar to those of SemFeel (Yatani and Truong, 2009), but without an extra damper (i.e., without a big sponge).
- Instead of tracking an active LED marker (Fiannaca et al., 2013; Folmer and Morelli, 2012; Li et al., 2009) or using an accelerometer and a gyroscope to sense the position and orientation (Li et al., 2010) of the hand, our system tracks hand movements without any additional hardware by using well-established computer vision techniques that can be applied outdoors. Also, while other systems require an actuator glove for tactile cueing (Lehtinen et al., 2012), our present study uses a mobile phone to create the directional vibrotactile flows for spatial cueing without the need to wear a glove or any special equipment, providing more convenient interaction experiences.

3. Design rationale

When searching targets in enclosed spaces, people can either search an area by systematic movement or random exploration. Systematic search patterns include zigzag, parallel sweeps, expanding square, and Archimedean spiral movements (Morash, 2015). In contrast, random searches can be categorized as Ballistic, Levy, and Brownian according to the way movement directions change (James et al., 2008). In animal ecology and operations research, it is shown that foraging with systematic search patterns is more efficient than random searches due to a better chance of avoiding the previously searched areas (Viswanathan et al., 1999; James et al., 2008; Banks et al., 2009). In addition, Morash (2015) reported that untrained blindfolded participants spontaneously used systematic search strategies during one-hand haptic search tasks on an unstructured tactile map. Although previous research examined the prevalence of systematic search patterns on two-dimensional haptic displays (Morash, 2015), less work has been done on the use of vibrotactile feedback for systematic mid-air search strategies. At the beginning of our research, we conducted a pilot study with three participants with visual impairments. We asked them to find a marker after we put the marker on a whiteboard. Two of them swept the whiteboard by going from the right edge to the left edge. The third person started the search from where the hand happened to be in space and extended randomly outward. These observations inspired our design of three target-finding methods. To support a systematic mid-air search strategy for a public large display, we utilize two forms of short distance geometry, Manhattan distance and Euclidian distance, by using up and down, left and right, and inward and outward vibrotactile patterns. The Cruciform search strategy utilizes Manhattan distance in order to support the parallel sweeps search pattern with left/right and up/down vibrotactile feedback, and the Radial search strategy utilizes Euclidian distance to support the Archimedean spiral systematic search pattern with inward/outward vibrotactile feedback.

In addition, we identified a number of relevant design rationales of an assistive interface for a large vertical display, which supports its possible use by people with visual impairments in a public space:

3.1. *Gestural interaction*

As public display sizes increase and the display is designed for viewing from a distance, it becomes necessary to enable interactions at a distance, such as using mid-air gestural input.

3.2. *One-handed operation*

During our initial interview, participants with visual impairments commented that it is hard for them to use a multi-touch screen because they usually have to carry something (e.g., a cane). The operation of the public display should therefore be easily achieved with one hand so that users with visual impairments' other hand can continue to use a cane for walking and sensing the surrounding environment.

3.3. *Haptic feedback*

Haptic feedback is a good way to interact with large displays in noisy public environments (Hoggan et al., 2009) and to navigate graphical contents such as maps, diagrams, and floor plans on those displays (Goncu and Marriott, 2011; Wall and Brewster, 2006).

3.4. *Use of mobile phones*

Because many of people with visual impairments carry mobile phones at all times (Kane et al., 2009), mobile phones are becoming even more popular commodities. Thus, one promising way of getting feedback from a large public display is through a mobile phone.

3.5. *Easy-to-find guideposts*

When people with visual impairments search the entire display to find a target, they can easily miss the target even though they are close to it, or they might revisit an area that has already been explored. To avoid such inefficiencies, an easy-to-find guidepost or a reference path to the target should be provided, so that people with visual impairments can know whether they are moving the cursor in the right direction towards a target.

3.6. *Customized guidepost*

To interact with a large vertical display, people with visual impairments may position themselves anywhere in front of the display. Sometimes they may not be facing the display directly. Therefore, the system should be aware of each user's position and orientation and support the user with a customized guidepost, based on his/her current position and orientation.

3.7. *Avoid hard-to-reach areas*

Given the users' height and the elevation of the display, people with visual impairments may not be able to easily access all areas on the large vertical display. Therefore, placing important or frequently used information in hard-to-reach areas should be avoided.

4. Vibrotactile guidance

In our target-aiming techniques, guidance cues are provided by means of vibrotactile stimuli produced on a mobile device held in the pointing hand. An intuitive approach to delivering such directional guidance is spatial coding, wherein a movement direction is represented by the location of vibrotactile stimulation or its positional changes over time. Humans have well-defined innate mapping instincts between the stimulated body site and its corresponding egocentric orientation (Choi and Kuchenbecker, 2013). However, since mobile phones are made of rigid materials and vibration is propagated along their surface, using localized stimulation sites for directional cues is not feasible. A workaround solution is to use an external damping mechanism as in SemFeel (Yatani and Truong, 2009) and SpaceSense (Yatani et al., 2012). Both systems use a custom sleeve that embeds multiple vibration motors on the back of a mobile device to isolate vibrations. In this case, directions can be represented using either apparent motion (a series of discrete vibrations that invoke the sensation of continuous motion on the skin) as in SemFeel or position-to-exocentric direction mapping (e.g., top-right vibration actuator indicates north-east) as in SpaceSense.

Another alternative is to rely on *vibrotactile flows*, which refer to vibrotactile sensations moving from one end of the device to the other (Seo and Choi, 2010). Vibrotactile flows provide the sensations of a continuously moving point on the user's hand holding a mobile device. In particular, vibrotactile flows in one direction can be generated by using just two actuators. Our design uses four actuators to represent four different directional cues, as illustrated in Fig. 2a. In this setup, vibrotactile flows can be generated in four directions, upward or downward using the top and bottom actuators and leftward or rightward using the left and right actuators. Vibrotactile flows and SemFeel elicit similar continuously moving vibrotactile sensations, but vibrotactile flows do not require additional vibration damping mechanisms, leading to higher practicality.

Vibrotactile flows in each direction are rendered using the two actuators at the corresponding starting and ending positions. For this purpose, any of the three methods can be used: amplitude inhibition (Seo and Choi, 2010), time inhibition (Kim and Kim, 2012), and amplitude inhibition with frequency sweep (Kang et al., 2012). We used amplitude inhibition because it is simple and its perceptual effects are relatively well known (Seo and Choi, 2013). In this method, each actuator generates a sinusoidal vibration with the same frequency, and the intensity of an actuator at the starting position is monotonically decreased and the intensity of an actuator at the ending position is monotonically increased, using the following synthesis equations (Seo and Choi, 2013):

$$a_1(t) = a_{max}\left(\frac{t}{T}\right)^{\gamma},$$

$$a_2(t) = a_{max}\left(1-\frac{t}{T}\right)^{\gamma}$$

where $a_1(t)$ and $a_2(t)$ are the respective accelerations of two actuators at time $t \in [0, T]$. a_{max} is the maximum acceleration, and T is the flow duration. Here, $a_1(t)$ is monotonically increased as $a_2(t)$ is monotonically decreased. This equation results in a vibrotactile flow linearly moving from the position of actuator 2 to that of actuator 1. The γ parameter determines the increasing/decreasing rates of the two vibrations and also has an effect on the overall perceptual attributes of vibrotactile flow, such as perceived travel distance and the confidence of flow-like sensation (Seo and Choi, 2013). After several pilot tests with blind users, it was empirically tuned to use $\gamma = 0.65$, which allows for the perception of a smooth directional movement. For more robust identification, we provide an identical flow twice with a short inter-stimulus interval (0.3 s) as shown in Fig. 3. This consists of a vibrotactile stimulus for one guidance cue.

When the user changes the movement quickly, a vibrotactile cue can be initiated even if the play of the preceding cue has not yet finished. If this occurs, we stop the preceding cue immediately, and then play the following cue. To help the users distinguish the change, a short strong vibration (0.1 s, a_{max}) is provided between the two cues using the actuator at the top of the mockup. Since the perceived direction of flow depends on hand orientation, the user needs to maintain his/her grasping posture and orientation consistently, and this is a natural behavior observed during the experiment.

It is noted that our design of vibrotactile flows uses constant amplitude, indicating only direction to the target, but not the distance to it. Although the amplitude of vibrotactile flow might be related to the latter in a proportional guidance scheme, we did not take that approach for several reasons. First, the human sensitivity to vibration amplitude is poor (just-noticeable difference about 10–30%; Choi and Kuchenbecker, 2013). Second, the output range of general vibrotactile actuators used in mobile devices allows for only two or three levels of vibration amplitude for reliable identification (Ryu et al., 2010). Third, using low-amplitude vibrotactile flows has a possibility of disturbing the perception of vibration movement direction. Our design of vibrotactile flows emphasizes maximizing their identification rate.

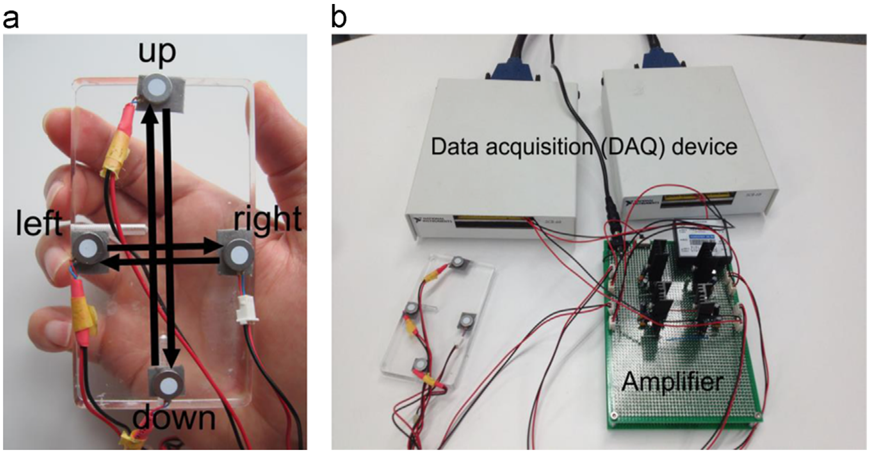

Fig. 2. Vibrotactile handheld device mockup used in Experiment 1.

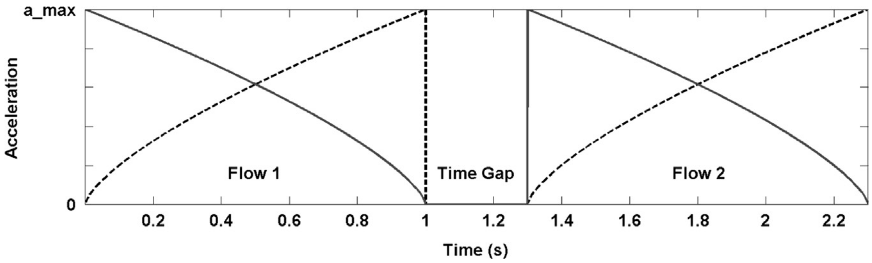

Fig. 3. Plots for the vibrotactile directional flow. Solid lines represent the amplitude of the actuator at the start location and dotted lines are for the actuator at the arrival location.

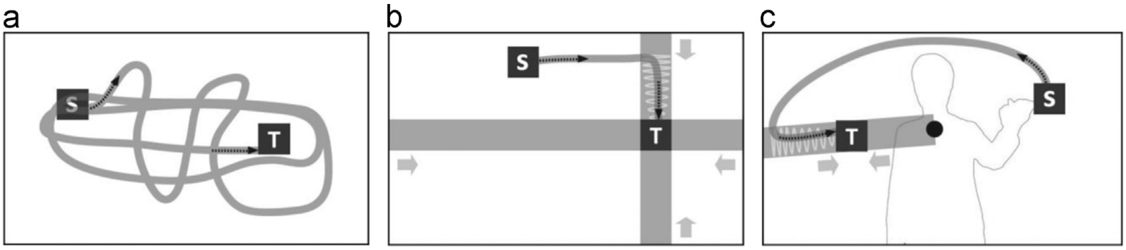

Fig. 4. Three target-aiming techniques. S is a starting point and T is a target. The curved line shows the trajectory of the pointing hand. Gray areas in (b) and (c) are where directional vibrotactile feedback is provided to the user in the direction of the gray arrow. (a) Random technique, (b) Cruciform technique, and (c) Radial technique.

5. Three target-aiming techniques

We compared three target-aiming techniques to help people with visual impairments aim at a target on a large vertical display. The techniques are Random, Cruciform, and Radial (Fig. 4). In all of them, users interact with the display using mid-air gestures while guided by vibrotactile feedback on a mobile device which is held in their pointing hand.

5.1. Random technique

This is a freestyle search in which users move the hand randomly in the air to aim at a target, receiving no guidepost to the target position. Microsoft Kinect's skeletal tracking supplies the coordinates of hand and wrist positions, which are used to calculate a ray-casting vector along the same direction as a projected line from the wrist to the hand. This allows the user's unrestricted hand movement to control the cursor on the display in a congruent manner for target selection. If the hand touches a target, the user receives confirmation feedback by means of a short vibration from the mobile device and a bell tone. The Random technique worked as a baseline for our experiment and was experimentally compared with our two enhanced target-aiming techniques below.

5.2. Cruciform technique

With a flat-screen tabletop computer, blind users showed preferences for touch-based input gestures that used screen corners and edges as landmarks (Kane et al., 2011). However, with a large vertical display, access to the edges of the display is not always feasible. Given the users' height and the elevation of the display, users with visual impairments may not be able to easily access the edges of the display. To compensate for people with visual impairments' limited access to the edges of a large vertical display, but still to make use of the benefits of *linearization of the search* (Kane et al., 2011), we devised the Cruciform technique.

The Cruciform technique extends a target location by stretching its x-position horizontally and y-position vertically, making the two vibrotactile feedback areas intersect at the target (Fig. 4b). As a result, users do not need to slide their hand along the edges of the display to access the target. Instead, they can move their hand horizontally or vertically from its current position until it reaches the vertical or horizontal extension of the target. When this occurs, the haptic device delivers vibrotactile guidance in the direction of the target from the current hand position, which is leftward, rightward, upward, or downward. Then, the user moves his/her hand accordingly. When the pointing hand reaches the target, the user feels the same feedback as that of the Random technique for successful target selection.

5.3. Radial technique

The Radial technique adopts a compass metaphor in guiding the user's hand towards the target. This technique provides a guidepost from the center of the user's shoulders. The user starts by drawing a circle in the air to find a direction to the target from the center of the two shoulders. If the user points along the direction to the target, the mobile device delivers one of two kinds of vibrational feedback (i.e., outward or inward) depending on the current hand position relative to the target position: if the target is located inside the user's hand movement, the inward vibrotactile feedback will be delivered and the user contracts the arm accordingly to reach the target (see Fig. 4c). Otherwise, if the target is located outside the user's hand position, the outward vibrotactile feedback will be delivered and the user needs to stretch out the arm to reach the target. Furthermore, if the target happens to be located at the right center of the shoulders, inward feedback will be delivered from the position of the hand at the beginning, because the target is located in the center of a circle.

Inward and outward vibrations are delivered by pairing actuators (e.g., top and left actuators and bottom and right actuators). If the hand moves outside of the active region, the stimuli for guiding the user will stop, and when the hand enters in the right direction to the target, the directional vibrotactile feedback is generated again. When the pointing hand reaches the target, the user feels the short vibration and hears the bell tone, as with the other two techniques.

The Cruciform and Radial techniques reduce 2D search dimensionality to two linear searches of a Euclidean coordinating system (x and y) or a polar coordinate system (angle Θ and distance ρ). This mapping allows users to first select a ballpark target area and then to locate it more precisely. The Radial technique supports each user with a customized guidepost towards the target, based on his/her height and standing position in front of the display, while the Cruciform technique provides a general guidepost for all users regardless of their height or position.

6. Experiment 1: comparison of the three target-aiming techniques

We evaluated the three target-aiming techniques with 11 participants with visual impairments. The Random technique worked as a baseline against which the other two target-aiming techniques were compared. We also examined whether participants could improve their target aiming by repeating three blocks of trials.

Table 1
Descriptions of participants.

	Sex	Age	Onset of blindness	Causes of blindness	The degree of blindness	Handheld devices
1	M	77	Infant	Congenital	Totally blind	Mobile phone for elderly
2	M	73	20	Glaucoma	Totally blind	Mobile phone for elderly
3	M	42	Infant	Congenital	Distinguish only light and dark	Smartphone, cane
4	F	49	Infant	Ametropia	Able to see shape but unable to distinguish	Mobile phone, magnifier, cane
5	M	68	25	Traffic accident	Distinguish only light and dark	Mobile phone, cane, talking pedometer
6	M	25	Infant	Unknown	Able to see shape but unable to distinguish	Mobile phone, magnifier
7	M	40	Infant	Hereditary	Able to see shape but unable to distinguish	Mobile phone, cane
8	M	68	25	Retinitis pigmentosa	Totally blind	Mobile phone, cane, audio compass
9	F	74	3	Unknown	Totally blind	Mobile phone, cane
10	F	59	5	Sickness	Totally blind	Mobile phone for elderly, FM radio, cane
11	M	63	Infant	Congenital	Distinguish only light and dark	Mobile phone for elderly, pedometer, braille reader

6.1. Participants

All eleven participants with visual impairments were right-handed, and three of them were females. Their ages ranged from 25 to 77 years. The mean age was 58 years. According to the World Health Organization (WHO, 2015), 82% of people living with blindness are aged 50 and above and senior citizens can be potential users of our system. Table 1 contains the demographic information of participants. Seven early-blind and four late-blind users participated in the experiments. The early-blind group consisted of congenitally blind people and individuals who had become blind before the age of three. They all have mobile phones: six have a regular feature phone; four have a mobile phone for the elderly, which has large text and buttons; and one has a smartphone. We recruited them via announcements through a local association for the blind. They were paid $50 for the half-day visit.

6.2. Apparatus

We used a large SHARP Aquos 60-in. (138 cm × 89 cm) flat LED display hung on the stack at eye-level for users in the standing posture. The display resolution was fixed at 1920 × 1080, and the refresh rate was 60 Hz. The experimental software ran on a 3.60 GHz Intel Core i7 workstation with Windows 7 Enterprise OS and a Kinect Windows SDK. A Microsoft Kinect camera was placed at the bottom-center of the display for gesture recognition.

The participants held a vibrotactile mobile phone mockup ($11 \times 6 \times 1$ cm^3, 95 g; Fig. 2a) made of acrylic resin in their pointing hand. Four linear resonant actuators (LRAs; LG Innotek MVMU-A360G), typically used in commercial mobile phones, were attached to the front face of the mockup. The maximum acceleration was around 0.68 G with a nominal resonance frequency 175 Hz, and this frequency was used to make sinusoidal vibrations for vibrotactile flows. The LRAs were powered by a custom-made amplifier connected to a data acquisition card (National Instruments, PCIe-6363, Fig. 2b) inside a workstation at 10 kHz sampling rate.

6.3. Setup and procedure

In the beginning, the participants were briefed about the study and asked to sign an informed consent form. We used a low-fidelity cardboard mockup to teach them how to use the three target-aiming techniques. During the main experiment, the participants stood in front of the display around 2.0 m away, where they could point to the entire area of the display with ray-cast pointing using mid-air hand gestures. They used their dominant hand for mid-air hand gestures. The Kinect camera detected the movement of the hand and mapped it to the cursor on the display for target selection. We also asked the participants to hold the mobile phone mockup tightly in the palm of the pointing hand and maintain their grasping posture and orientation consistently throughout the experiment.

The targets used were squares of three different sizes: small (3.5×3.5 cm^2), medium (5×5 cm^2), and large (7×7 cm^2). Another square (10×10 cm^2) positioned at the center of the display was used as the starting point. The smallest size (i.e., 3.5 cm^2) was empirically tuned through a pilot study so that it would not be too small for blind participants to find. The visual angles based on the distance from the participants (i.e., 2.0 m) are about 1.0° for the small target, 1.5° for the medium target, and 2.0° for the large target. The experimenter helped participants position the cursor over the starting point at the beginning of the trial. On each trial, only one target showed up in random positions on the display. Each participant repeated the target-aiming tasks with three sets of blocks. As a result, a total of 297 trials were conducted for data collection (11 participants × 3 target-aiming techniques × 3 target sizes × 3 blocks). Within each block, the order of target-aiming techniques and target sizes was randomized and counter-balanced using Latin squares respectively. Participants had at least three practice runs before conducting each target-aiming technique condition to become accustomed to each technique and the system. There was a short break between blocks. After all tasks were completed, the participants answered questionnaires about their experience and had a follow-up interview. We gathered experimental data with a number of participants, and the result of power analysis showed that the study had sufficient power (i.e., greater than.80) to detect any significant effects. The participants with visual impairments took enough rest between blocks and the whole experiment took about 2 hours including questionnaires and a follow-up interview.

6.4. Results

We analyzed performance in terms of target finding time and failure rate. A repeated-measure three-way analysis of variance (ANOVA) was used with the three factors of target-aiming techniques, target sizes, and block number. For subjective preference analysis, a Friedman test was used. All tests were run at a significant level of $\alpha = 0.05$.

6.4.1. Target finding time

Target finding time was defined as the duration from the moment when the pointing cursor left the starting square to the moment the cursor entered the target square. We observed that some participants revisited the target in a few second either by reacting slowly to confirmation feedback or because of trembling hands. In those cases, the first entry moment into the target square was recorded. The target-aiming technique had a significant effect on the mean target finding times ($F(2,20) = 15.92$, $p < 0.0005$). The overall mean target-finding times were 30.6 s (Standard Error (SE) = 4.0 s) for Random, 16.3 s (SE = 2.1 s) for Cruciform, and 14.9 s (SE = 1.8 s) for Radial. Post-hoc pair wise comparisons showed that both Cruciform and Radial were significantly faster than Random ($p < 0.01$ and $p < 0.001$, respectively). However, no significant difference was found between Cruciform and Radial.

Repeating the tasks in three blocks helped the participants improve their target-finding time. However, the p-value approached but did not reach statistical significance ($p = 0.053$). The mean target-finding times were 25.1 s (SE = 4.0 s) for the first block, 19.9 s (SE = 2.0 s) for the second block, and 16.8 s (SE = 2.0 s) for the third block. Fig. 5 shows the mean task completion times for the three target-aiming techniques over the three repeated blocks. The Radial technique showed a trend to be faster than

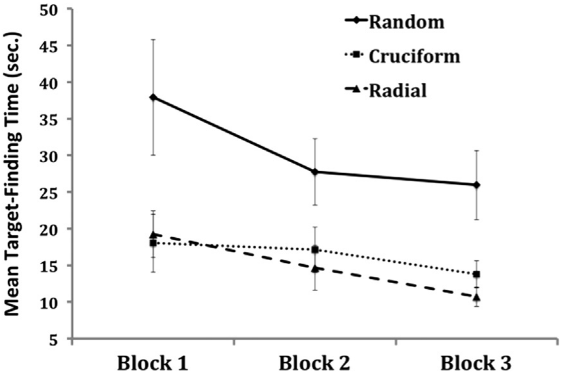

Fig. 5. Mean target-finding times for three target-aiming techniques. Error bars show ± standard error.

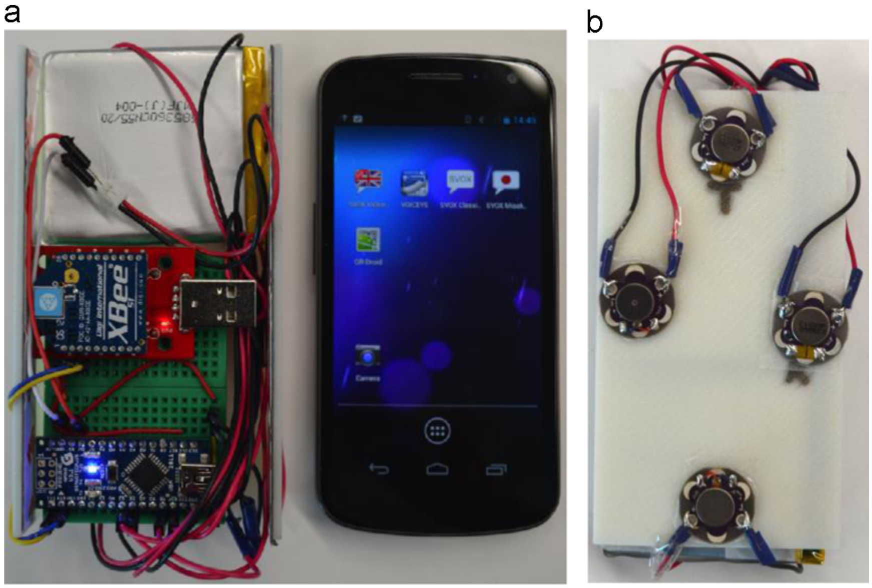

Fig. 6. Vibrotactile handheld device mockup used in Experiment 2: (a) inside of the haptic module box and (b) back of the box.

Cruciform as participants repeated the tasks, but did not reach statistical significance.

Target size had no significant effect on the results. It took an average of 25.7 s (SE=3.8 s) to aim directly at the small target, 18.1 s (SE=2.2 s) to aim at the medium target, and 18.0 s (SE=3.2 s) to aim at the large target.

6.4.2. *Failure rate*

During all the trials, there was only one case where the participant failed to find the target within the specified time limit (3 min). This occurred when the participant tried to aim at a small target using the Random technique.

6.4.3. *Subjective preferences*

We composed five questions by referring to the ISO9241-400 evaluation questionnaire, such as learnability, easy of use, physical demand, mental demand, and desire to use (ISO, 2007). Results revealed no statistically significant difference in any of the questions among the three techniques. However, participants generally answered favorably in the following order: Radial, Cruciform, and Random.

7. Experiment 2: comparison between speech and haptic feedback

Inspired by the results of Experiment 1, we examined a real-world usage scenario with the Radial technique in Experiment 2. The context was a large wall-mounted display that presented a train schedule table and a barcode beside the table for people with visual impairments. Participants could hear a voice announcement for the train schedule through their phone by pointing a smartphone towards the barcode. In order to do that, the Radial technique guided the participants to correctly point to the barcode so that the barcode reader app, running on the smartphone, could scan this machine-readable optical label and convert it to speech.

Specifically, we compared the effect of haptic feedback with that of speech feedback on the Radial technique. Experiment 1 showed that the Radial technique tended to be the best among the three target-aiming techniques. Thus, the Radial technique was configured with three different feedback conditions: (i) speech, (ii) haptic, and (iii) speech+haptic. If the hand was aligned with the direction to the barcode and the barcode was positioned outside (or inside) the circle drawn by the hand, participants would hear a voice command “outward” (or “inward”) in the speech feedback condition, or feel an outward (or inward) vibrotactile flow in the haptic feedback condition, or hear the command and feel the vibrotactile flow simultaneously in the speech+haptic feedback condition. Correspondingly, participants needed to move the hand outside (or inside) to select the barcode.

7.1. *Participants*

We recruited ten participants with visual impairments for Experiment 2. All participants were right-handed and three were females. Their ages ranged from 26 to 77 years. The mean age was 54 years. They were paid $50 for their participation.

7.2. *Apparatus*

We used the wall-mounted 60-in. flat display and the Kinect camera as in Experiment 1. To support barcode reading, we installed a freely downloadable Voiceye™ app[1] on an Android phone. By scanning the barcode using a camera on the smartphone, the Voiceye™ could convert the information contained in the code to various methods of access including voice and braille. The Voiceye™ also supports encoding information on the barcode as a voice memo or a text memo. We encoded the voice memo so that the next train schedule information could be played when participants scanned the barcode using the smartphone.

For haptic feedback, we remodeled the mockup to be wireless. Fig. 6 shows the new haptic feedback device used in Experiment 2. The XBee sensor network module was built for communication between the display and the handheld mockup. The vibrotactile handheld mockup consisted of four LilyPad vibe boards, an Arduino Nano, a mini breadboard, and a polymer lithium-ion battery. They were all placed together inside a 3D-printed small box, which could fit into the back of a smartphone (Fig. 6a).

The LilyPad vibration actuators are standard vibration motors, another type of common commercial vibration actuators. When amplitude inhibition is used with these actuators for vibrotactile flow rendering, both perceived signal intensity and frequency

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[1] http://www.voiceye.com

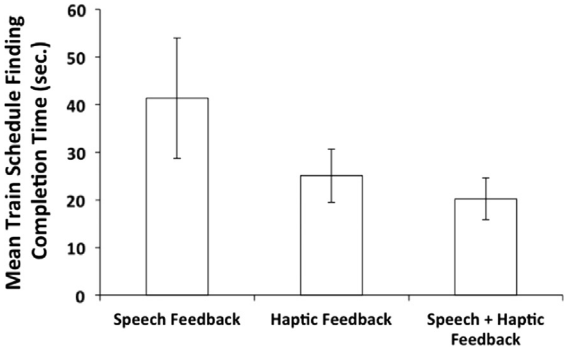

Fig. 7. Mean finding times for three feedback. Error bars show ± standard error.

increase with the power applied to the actuators. This effect is similar to amplitude inhibition with frequency sweep, which provides smooth sensations of movement (Kang et al., 2012). Since the LilyPad vibe boards used pulse-width modulation (PWM), we controlled the duty cycle of control signals sent to the actuators.

7.3. Setup and procedure

Using a smartphone where the haptic mockup was attached to the backside, the participants were asked to point towards a barcode label (10 cm × 7 cm) that was located in either the top-right area, the top-left area, or the bottom-right area of the display. These were just general areas for target positioning and the exact positions of the targets during the experiment were varied to minimize a learnability/familiarity bias. We decided not to test the bottom-left area because the participants found it hard to reach this area in Experiment 1. Speech feedback for the direction, which was the voice command “inward” or “outward”, was activated only once at the moment when the hand entered the direction to the label (i.e., gray areas in Fig. 4c). By contrast, the haptic feedback was activated while the hand remained pointing along the direction to the target. For the speech+haptic feedback, voice guidance and vibrotactile flow were activated simultaneously. When the barcode was finally reached, participants could hear the voice announcement of the next train's arrival time through the smartphone they were holding.

Participants started searching for the barcode upon hearing a “start” voice command from the system, as they raised the left hand. They used their dominant hand (i.e., the right hand) for target acquisition. Each participant conducted the barcode-aiming tasks with a full combination of feedback and barcode position areas. Therefore, a total of 90 trials was carried out for data collection (10 participants × 3 feedback × 3 areas). The order of conditions was counterbalanced using Latin squares. Participants had at least three practice runs to become familiar with each feedback system before each trial. After all tasks were completed, the participants answered questionnaires about their experience and had a follow-up interview. The whole experiment took about two hours.

7.4. Results

A repeated-measure two-way ANOVA was used with the factors of feedback type and target barcode position. For subjective preference analysis, a Friedman test was used.

7.4.1. Train schedule finding time

Fig. 7 shows the mean train schedule finding times for the three feedback conditions. Train schedule finding time was calculated as the duration from the moment when the “start” voice was played to the moment the next train arrival time information was announced. The train schedule finding time differed significantly among the feedback conditions ($F(2,18)=4.85$, $p=0.021$). The overall mean finding times were 41.3 s (SE=12.7 s) for speech feedback, 25.1 s (SE=5.6 s) for haptic feedback, and 20.2 s (SE=4.4 s) for speech+haptic feedback. Post-hoc pairwise comparisons showed that the speech+haptic feedback was significantly faster than speech feedback ($p=0.045$). However, no significant differences were found between speech and haptic ($p=0.07$), or between haptic and speech+haptic ($p=0.113$).

The area of the barcode position had a significant effect on the results overall ($F(2,18)=6.27$, $p=0.009$). It took an average of 17.0 s (SE=3.4 s) to aim at the barcode in the top-left area of the display, 28.0 s (SE=7.2 s) to aim at the barcode in the top-right area, and 44.7 s (SE=12.7 s) to aim at the barcode in the bottom-right area. Post-hoc pairwise comparisons showed that searching the barcode in the top-left area was significantly faster than searching the barcode both in the top-right area and in the bottom-right area (for each, $p=0.03$ and $p=0.02$). However, no significant difference was found between searching the barcode in the top-right area and in the bottom-right area.

7.4.2. Failure rate

There were only two trials in which participants were not able to find the barcode within the specified time limit (3 min). These were under the speech only feedback condition.

7.4.3. Subjective preferences

The questionnaire consisted of five questions, composed by referring to the ISO9241-400 evaluation questionnaire (ISO, 2007). The results showed that there was no statistical significance in any questions among three feedback conditions. However, the speech+haptic feedback was the most popular, and five out of the ten participants chose the speech+haptic feedback as their most preferred feedback condition.

8. Discussion

Cases exist that require people with visual impairments to physically aim at a target on a display, even after the system has detected what the user wants; for example, showing an identification badge at the entrance or retrieving a travel guide by aiming a device at a QR code on signage without needing network configurations between the two, or wirelessly charging batteries by pointing to a hotspot at a kiosk. Guiding users with visual impairments to effectively aim at a target on a large vertical display is important, yet haptic guidance for aiming interaction has not been studied much. Our work is one of the first attempts to develop an interface that facilitates efficient aiming at a target on a large vertical display using vibrotactile feedback by users with visual impairments.

Kim and Ren (2014) had the same motivation of assisting visually impaired people to interact with a large wall-mounted display. They conducted experiments with the Fitts and steering tasks on a large vertical display, and found that Fitts' law could be applied for blind-folded users in their experiments. Fitts task and the steering task are good examples in which we still need to guide the hand to the target in spite of the users' approximate knowledge of the target position. There may exist many alternatives for target selection by people with visual impairments such as speech commands, but effective target selection by the hand is also another important interaction technique that we should consider with potentials that require testing and evaluation.

We have presented two target-aiming techniques (Cruciform and Radial) and a basic technique (Random) for navigating a large vertical display using mid-air input gestures and vibrotactile feedback. The experimental results show that simple target-aiming algorithms with a relatively inexpensive haptic device significantly improved our participants' performances in terms of target-finding time. Participants were able to aim at the targets more quickly when a guidepost was provided (as in Radial and Cruciform) than in Random, which had no guidepost. Overall average subjective preference scores were decisive in the following order: Radial, Cruciform, and then Random.

For the Random technique, participants were instructed to use any strategies they liked. We observed that they often revisited the area that had been already explored, or missed the target even though they were close to it. One participant commented that at least the edges of the display should have been encoded through vibrations in the Random technique, so as to indicate the operating range. This suggests the importance of guideposts or reference paths that can assist visually impaired people to make positive progress towards a target on a large vertical display. Our approach of a geometrical conversion of 2D search area into a series of the linear can be extended for other search problems.

Our Cruciform technique differs from edge projection in Kane et al. (2011) in that our users do not need to find the edges, the feedback in our study is haptic not auditory, and we allow ray-cast pointing with mid-air gestures instead of touch interactions. During the interview, our participants commented that, when interacting with a large vertical display, they felt that gesture input would be more convenient than direct touch because it is not always easy for people with visual impairments to know the distance from a display, nor how to approach it. With gestures, however, they could potentially interact with a large display from a distance. In addition, the purpose of the Cruciform technique is different from multi-linear scanning in Fiannaca et al. (2013) and Folmer and Morelli (2012), which helps sighted participants acquire targets in virtual spaces. As shown in Li et al. (2010), sighted and blind participants perform differently in eyes-free target selections. By contrast, our work focuses on target acquisition on large vertical displays by participants with visual impairments.

In Experiment 1, participants were generally more favorable to the Radial technique than the Cruciform technique. However, we would imagine that Cruciform would be preferred for something like a grocery store map, which is more or less organized on a Euclidean coordinate system. The Radial technique may be more preferable in a picture-based search scenario where there is no clearly defined city-block or polar coordinate system. Since Experiment 1 was conducted without any usage context and the difference between the Radial and Cruciform technique was not significant, it might be interesting to investigate whether Radial and Cruciform would cause different performance results in the grocery store map context.

We conducted a controlled, lab-based experiment to investigate the effects of vibrotactile assistive interfaces. This controlled, lab-based experiment enabled us to simplify many issues that would arise in real world contexts and therefore to focus on the effectiveness of the vibrotactile feedback in target-aiming tasks. For example, in our study, the distance to the display and the optimal working space required by the current Kinect system were controlled not by the participants themselves but by the experimenter. To further demonstrate the effects of our assistive system, it is desirable to conduct long-term, in the wild studies as future work.

The result of Experiment 2 showed that participants were able to aim towards the target about twice as fast by augmenting speech feedback with haptic feedback. Furthermore, speech + haptic feedback was preferred presumably because the speech indicated the direction of further movement and the vibration feedback guided the participants towards the target. Previous studies showed that interference from background noise could significantly reduce the effectiveness of the auditory channel in a public environment (Hoggan et al., 2009). One of our participants has poor hearing because of aging. In those cases, haptic feedback provides a viable option, complementing audio feedback.

It seems audio must be a part of accessible large screen interfaces, as audio is necessary for providing precise information about the content of the screen. In Experiment 2, based on the comparative haptic directional design, speech feedback was rendered using everyday speech, which sighted people and blind people could hear equally well. Although the current results do not show a clear benefit ($p=0.07$) of vibrotactile feedback over speech feedback in delivering directions to desired locations, it provides important implications regarding the value of vibrotactile feedback as a supplement to voiceover commands in the design of content-navigation systems for users with visual impairments, especially in noisy environments. On the other hand, the enhanced synthesized speech feedback such as using timbre, pitch (Edwards, 1988), speed, word prosody, and spatial audio (Crispien et al., 1994) could have made our findings more competitive.

During the interviews, participants with visual impairments indicated that reliable people may not always be available to assist them in public places and it would not be easy for them to identify a helper. They wanted to access public displays on their own to increase their independence in public places. For example, they would like to have accessible public displays at a supermarket that can guide them towards specific sections for food or clothing. We would like to argue that if sighted people interact with a large display with a gesture-based interaction, then at least we should provide the same interaction mechanism to people with visual impairments. The ACM code of ethics (2015) states, "In a fair society, all individuals would have equal opportunity to participate in, or benefit form, the use of computer resources regardless of race, sex, religion, age, disability, national origin, or other similar factors." We cannot get rid of any option by ourselves simply because we assume they may not need it. Whether they accept that specific option or not should be decided by them. This work demonstrates a successful interface that can be utilized by people with visual impairments for interaction with a medium that in its traditional form is not currently accessible to them.

In terms of hardware, our approach is a simple and inexpensive extension using off-the-shelf actuators and a commonly available camera-based tracking system. Although most smartphones typically feature a single vibratory motor nowadays, RIM has introduced BlackBerry Storm2 (2009), which is the first smartphone to have a full clickable touchscreen powered by four piezoelectric actuators on the four corners of the screen. Likewise, if necessary, our approach using four actuators in a mobile phone for creating vibrotactile feedback could become more popular in the future.

In our experiments, the systematic search strategy with vibrotactile feedback generally performed better than random/non-systematic search and enhanced speech feedback. These results encouraged the exploration of vibrotactile feedback in systematic searches, which is not only related to haptic perception indicating whether the target is touched or not, but also offering guidance regarding how the hand and arm can be moved toward the target. Our current haptic design provides only directional guidance but not a proportional cue or an error correction scheme where the amplitude of a vibration is directly proportional to how far the user's hand is from the target. If vibrotactile feedback for error compensation were added, it might be more efficient than the current design. The other possible expansion of our proposed search method on a large 2D display is to search/feel 3D spatial information by building a small cube to be held in the hand or in both hands in order to deliver directional cues in 3D.

Previous studies have indicated fatigue (e.g., the guerilla arm syndrome) in spatial interfaces; Gestures in a relatively fixed frame-of-reference in free space can cause fatigue within as little as five minutes of use (Hinckley et al., 1994). In our experiments, few cases (only three trials) failed to find the target in the limited time (i.e., three minutes) and fatigue was a negligible problem. Furthermore, we expect our spatial interaction to be shortly used for initiating more intense interactions, which will follow with multisensory feedback including auditory feedback. As future work, nevertheless, further empirical studies of fatigue in mid-air gestures aided by vibrotactile feedback are necessary for users with visual impairments.

9. Conclusion

The rapid growth of large interactive display systems in our daily lives enables sighted people to walk up and derive great advantages spontaneously and naturally. On the other hand, this technology remains largely inaccessible to people with visual impairments. In an effort to deliver the same benefits to people with visual impairments, we have explored the feasibility of gesture input and vibrotactile feedback to help them access targets on a large wall-mounted display. Our results confirm the potential of our proposed techniques to enhance the ability of people with visual impairments to access information on large interactive vertical displays. It is our aspiration that this initial work will serve as the first step towards granting them equal access to information on large public displays in the near future.

Acknowledgments

This study was partially supported by the Grant-in-Aid for Scientific Research of Japan under Grant nos. 23300048 and 25330241, and the National Natural Science Foundation of China under Grant no. 61228206, and the research grant NRF-2013R1A2A2A01016907 from the National Research Foundation of Korea.

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