Designing Media for Visually-Impaired Users of Refreshable Touch Displays: Possibilities and Pitfalls

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Abstract—This paper discusses issues of importance to designers of media for visually impaired users. The paper considers the influence of human factors on effectiveness of presentation as well as the strengths and weaknesses of tactile, vibrotactile, static pins, haptic, force feedback, and multimodal methods of rendering maps, graphs and models. The authors, all of whom are visually-impaired researchers in this domain, present findings from their own work and work of many others who have contributed to the current understanding of how to prepare and render images for both hard-copy and technology-mediated presentation of Braille and tangible graphics.

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1 INTRODUCTION

This paper provides an overview of how haptics can be useful for accessing information by people with visual impairment. The major focus is on the strengths and limitations of current technologies, and their potential for providing greater access to non-textual information. Such information is pervasive today in visual formats, but often inaccessible to people with visual impairment. Common examples include maps and graphics, dynamic simulations, 3D models, on-line presentation of statistics such as scores during sporting events and interactive models (e.g. models of climate change).

Complementing the explosion of interactive content is an expanding repertoire of refreshable touch display technology (e.g. tactile, vibrotactile and haptic displays) which have the potential to address this access gap. Blind people, people with dyslexia, people with reduced visual acuity due to age-related eye diseases such as macular degeneration, and many other segments of the population can benefit from such technology.

In this paper, our aims are:

- to highlight some of the unsolved problems related to these displays,
- to consider the abilities of the diverse user groups,
- to describe what has been learned about the production of tactile graphics and haptic models for use by people with visual impairment,
- and to list the pros and cons of different forms of refreshable touch displays available for closing this accessibility gap.

Designers of touch displays can benefit from communication with end users with visual impairment, particularly feedback on the functionality of such displays. We note that the authors of this article, all of whom are visually impaired, have relevant expertise, and have drawn upon their professional and personal experience to guide the discussion.

This paper focuses on displays intended for the hands and fingers. Although we will not address the characteristics of tactile displays used as sight-substitution systems, such as the BrainPort, a tongue-display unit ([1], [2]), some of the issues discussed below are also relevant to such displays.

2 DIVERSITY OF THE VISUALLY-IMPAIRED POPULATION

While everyone can potentially benefit from some forms of enhanced touch displays, here we focus on their use to assist people with visual disabilities. Estimates of the prevalence of visual disabilities vary widely depending on criteria and methods [3]. According to statistics compiled by the National Eye Institute, there are approximately 4.2 million Americans with impaired vision over the age of forty [4], and the number is rising as the American population ages. Of these, approximately 1.3 million are legally blind (defined as corrected acuity of 20/200 or less) and 2.9 million have milder forms of impaired vision not meeting the criterion of legal blindness. No reliable data are available for the number of people who are totally blind, but it is thought that they comprise roughly 25% of the legally blind population. There is a substantial correlation between gender and incidence of visual impairment—with 66% of people with visual impairment being female and 34% male. This imbalance is associated with the greater longevity of women.

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The World Health Organization has recently estimated that there are 285 million people worldwide with visual impairment, 39 million who are blind and 246 million with low vision [5]. These worldwide figures include many people in less developed countries whose impaired vision is due to uncorrected refractive errors or untreated cataracts.

We suggest that younger people with impaired vision will particularly benefit from haptic technologies that support educational and employment opportunities because they will facilitate access to the rapidly increasing quantity of graphical displays of data in education and business. Older people will benefit as well in domains such as spatial navigation where map data can be used for wayfinding in combination with accessible GPS software. Attention to inclusive design for older people is important because of the increasing number of seniors, and because the most prevalent forms of eye disease are age-related, including macular degeneration, cataract, glaucoma and retinitis pigmentosa. The number of visually-impaired Americans is expected to rise dramatically during the next 15 years.

Many people with impaired vision have other coexisting health problems. People with age-related macular degeneration, for example, have high rates of depressive disorder [6] and cognitive deficits [7]. People with impaired vision from diabetes often also experience peripheral neuropathies resulting in decreased tactile sensitivity in the fingers, hands or feet [8].

Aging may also affect utilization of refreshable touch displays. Haptics is usually thought to involve the tactile and kinesthetic systems and their integrated use in manual exploration [9]. Such exploration relies on both active and passive touch [10]. Passive touch refers to perception from cutaneous signals resulting from tactile stimulation of a passive observer. In contrast, active touch includes both the sum of bottom-up tactile stimulation and kinesthetic signals from movements of the hands or fingers.

Tactile acuity of sighted and most blind people decreases slowly but progressively with age [11], [12], [13]. This means that people who acquire impaired vision later in life are likely to have poorer tactile acuity than young adults. There is evidence, however, that people who are blind from an early age do not experience this progressive age-related decline in tactile acuity during active touch [14]. Several studies using modern psychophysical methods have demonstrated that tactile spatial resolution is better in blind subjects than age-matched sighted subjects [12], [13], [11], [14], [15], but see also [16] who did not find a blind/sighted difference.

More recently, Wong et al. [17] performed experiments to distinguish between the two competing hypotheses for the greater tactile acuity in blind people. The tactile experience hypothesis holds that greater reliance on touch promotes higher acuity, including retention over the life span. The visual deprivation hypothesis holds that greater tactile acuity is due to the absence of vision, independent of the history of tactile experience. Their experimental results favor the tactile experience hypothesis. They suggest that tactile experience may have an impact on somatosensory processing or on cross-modal cortical plasticity.

In short, there is diversity within the visually-impaired population who may benefit from improved nonvisual access to graphical or textual information, and there is a corresponding need for diversity in assistive technologies. Mainstream developers should strive for an inclusive, broad design of technology. The goal should be to extend the usability of mainstream products to the maximum number of people without sacrificing functionality or commercial viability. Modern mobile devices provide an excellent example. Most have speech input and output, use gestures, and can control magnification and contrast [18], thereby providing support for multiple approaches to accessing the same underlying functionality.

3 PERCEPTUAL CONSTRAINTS ON TANGIBLE MEDIA

The term “Tangible Media” here refers to any method of displaying information intended to be accessed with the fingers. One of the biggest challenges for designers of tangible media displays is to recognize the difference between vision and touch in the content of information transmitted. When equated empirically, touch has a lower spatial resolution and more restricted field of view than vision [19], [20]. When representing visual information tactually, it can be tempting to strive for a one to one correspondence between visual input and tactual output. Except for very simple displays, doing so actually leads to perceptually cluttered and unusable displays. We posit that effective tactual representation of visual information depends critically on understanding the perceptual differences between the two modalities and on appropriately representing the semantic content of the information. The specifics of the interface technology is a secondary issue, as evidenced by the myriad rendering approaches summarized below.

As mentioned above, there are some obvious perceptual differences between vision and touch that must be considered when designing effective haptic interfaces. Most importantly, visual information can generally be quickly apprehended and encoded from a display because of the combination of a large field of view and rapid saccadic eye movements. By contrast, the same content apprehended through touch requires far longer to explore with finger and hand movements. Tactual exploration is more difficult because of the greater demand on integrating information across space and time during prolonged exploration. Unfortunately, this integration is not always accurate, which complicates the comprehension of global structure [21]. This problem is exacerbated by the fact that many refreshable touch displays only allow the use of one finger as the primary point of contact, although it is known that the use of multiple fingers and both hands facilitates performance [22]. Feeling with one finger is analogous to viewing images through a narrow viewing window, and can be inefficient for the exploration of tactile images because blind people are taught to use their hands, not just fingers, to gain an overview of a tangible graphic before trying to discern its fine features.

Differences in spatial resolution between vision and touch must also be considered when designing effective tangible media displays. Recent measurements of spatial thresholds on the fingertip range from about 1.2 mm to 1.7 mm for young, normally sighted subjects, depending on the testing method and study. The thresholds for blind subjects are roughly 0.2 mm lower, ranging from about 1.0 to 1.5 mm, representing about 15% better tactile acuity (see [14], Table 1 for a summary). Since the finger pads themselves have a small surface area, the overall number of resolvable points with touch is miniscule compared to vision. The smaller effective field of view from touch means that the data being conveyed on a refreshable touch display will extend beyond the fingertip(s), requiring that it be encoded by a sequence of touches, which can introduce errors and illusions during exploration [23]. While this is most critical for haptic devices that provide only a single point of contact with a rendered surface, it is also true for other forms of shape and surface displays where the whole fingertip is in contact with the rendered image.

Take for example the coast of Maine, which has one of the longest coastlines in the lower 48 states due to its jagged and asymmetric envelope. If one were to take a standard visual map of Maine, such as the one shown in Fig. 1, and attempt to render this information via a similar-sized high-resolution physical 3D model (which represents the best possible medium for extraction of haptic information) it would still be impossible to provide a one-to-one rendering due to the differences in spatial resolution between the senses.

Although the use of efficient exploratory strategies can maximize information extraction [24], many of these strategies assume manipulation and handling of 3D objects and are not possible using most of the interface technologies discussed here. Tangible displays are inherently low information density displays, and since vision is conservatively estimated as having 500 times the sensory bandwidth of touch [25] it is critical to a priori consider what information in an image conveys the most meaning and to determine the appropriate amount of down sampling of visual input to tactile output that is required to create uncluttered displays. In general, following the 'less is more' mantra is the simplest way to ensure that a tangible display will be both meaningful and usable. This principle is implemented in successful production of hard-copy tactile images. Maps, scientific diagrams, and other informational graphics are usually converted to line drawings. To increase legibility, transcribers often expand the image scale, remove small features, and divide more complicated diagrams into multiple separate tactile graphics.

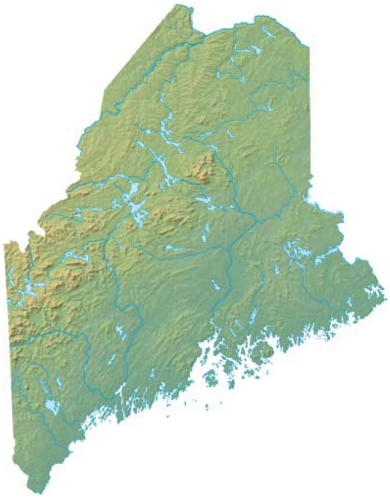

Fig. 1. An image of the coast of Maine, USA.

Another pitfall for tangible media display design is what is termed the "engineering trap". This occurs when design is driven by engineering principles or the technology itself, rather than being motivated by solid theoretical knowledge of the relevant perceptual and cognitive factors associated with use of the display and the tasks it is meant to support [26]. One example of the engineering trap is the appealing but misguided idea that one type of display technology can be used for all kinds of tangible graphics. Touch-based technologies differ widely in what and how information is being rendered, in what cues are perceptually salient, and in the types of tasks they best support. These factors are briefly summarized for several categories of technology in Section 4 below.

Designers are encouraged to think carefully about both the information they wish to present and how it is to be used when considering what technology is most suitable for their needs. For instance, vibro-tactile surface displays require three times the line width as compared to standard embossed tactile output to achieve similar tracing performance [27]. It is often difficult to stay oriented on curved or jagged lines using these displays [28], which means that this technology may suffer in situations where precise interpretation of high resolution, irregular lines is required (e.g., our example of the Maine coastline). Likewise, the information conveyed by electrostatic displays is motion-dependent, meaning that situations where a user must access the material without any hand/finger movement is impractical. As we will discuss, there are trade-offs for all these technologies but their ability to convey dynamically-updated and multimodal information also provides significant benefits over traditional static tactile renderings.

A good refreshable touch display for graphical material must go beyond accurate perception, it must also support accurate learning and representation of information facilitating subsequent mental transformations, computations, and behaviors. Fortunately, much of the relevant content conveyed by graphical material is spatial (e.g., points, lines, contours, and regions) and most of this spatial information can be conveyed by both tangible and visual displays. Indeed, a growing body of literature supports the notion that spatial information encoded from vision, touch, and other spatial modalities leads to the development of common, amodal representations in the brain which function equivalently in supporting spatial behaviors, irrespective of the modal source [29].

4 OVERVIEW OF REFRESHABLE TOUCH DISPLAYS

4.1 Generating tangible media

When considering how to generate tactile images, maps and even Braille using electronic means, the first question to ask is what classes of tactile percepts can we simulate using current technologies. Over the past 10 years, there has been a rapid increase in both the number of tactile and haptic devices in development and on the market and, more importantly, in the kinds of tactile effects they can produce. In this section, we will briefly review six main classes of devices, with respect to their potential to support the rendering of refreshable tangible images for visually impaired people.

Most refreshable touch displays rely on generating specific effects that stimulate only a subset of the mechanoreceptors in the skin, muscles and joints. This is because the variety and richness of mechanical stimulation available in the real world is far greater than any single device can currently produce. That such displays are successful at all is due to the robustness of the human haptic system and to the fact that there is a great degree of redundancy (or overlap) in the haptic cues provided by our interaction with the environment. Each class of display presented here depends on the presence of such redundant information in that each category provides a different but often suboptimal set of tactile and/or haptic cues relating to attributes such as texture, hardness, shape and so on. In many instances where these displays are used, such as enhancing flat screen displays or in medical simulation, visual cues are also available to aid in the perception of attributes such as object geometry. The question addressed here is whether, lacking support from the visual modality, such technologies are appropriate for the display of tangible media for visually impaired users. Can displays which at the outset provide access to only a subset of the haptic cues available during free exploration of hard copy tactile models or images serve to convey sufficient salient cues for the exploration of such media for blind users?

As stated earlier, transcribers who create hard-copy tangible media such as maps and charts often greatly simplify the visual image to reduce its complexity. In doing so, their aim is to match the most important information conveyed to the perceptual channels available to the visually impaired user, while also working within the constraints of the materials available for rendering (simple raised lines, layered paper constructs, 3D models, and so on.) The goal of the creator of such images is still to match the information to be conveyed with the haptic cues that can best support the rendering of the image, but now with the added requirements of accurately understanding and utilizing the rendering capabilities of the device to be used. It would be helpful, therefore, for the transcriber who wishes to render tangible media using any of these technologies to have at their disposal a set of specifications to guide them as they design their tangible images. While the following is not intended to function as such a set of specifications, our goal is to begin a discussion from which such design principles might emerge.

The most salient features of hard-copy tangible graphics are textures, contours and global shape. In free exploration of tangible graphics, therefore, we might expect users to employ the exploratory procedures (EPs) most optimal for extracting these features, that is, lateral motion (moving the fingers back and forth across a texture or feature), contour following (tracing an edge within the image) and whole-hand exploration of global shape [24]. One possible question to ask of each class of devices, therefore, is to what extent they support these three exploration strategies. In other words, can the user employ appropriate exploratory procedures for extracting texture, contour and shape information in a manner that resembles free exploration of hard-copy tactile images. As a thought experiment, for the technologies discussed below, think about how challenging it might be for a blind user to interpret the contour of our Maine coastline example.

4.1.1 Surface haptic displays

Surface haptic displays are defined here as those displays which rely on modulating the friction that is created when a fingertip is moved across a flat surface such as a glass or plastic screen. There are several techniques currently in development for modulating friction across the contact patch, e.g. using electrovibration as in the TeslaTouch [30] or by modulating electrostatic force as is done with the T-Pad [31]. Of note here is that all such displays result in the perception of areas of greater or lesser smoothness which in turn are typically mapped onto objects or features that are visible on the screen such as buttons, edges and textures.

By modulating the friction between the fingertip and a surface in a systematic way, surface haptic displays also modulate the amount of force that must be applied by a user to push their fingertip across the edge of a feature. In this way, such displays can be used to create the percept of geometric features on a surface that is actually completely flat. There are three important limitations of such displays that designers should note with respect to rendering tactile images. First, the majority of these displays are not yet capable of multi-touch, meaning that only one finger can be in contact with the display at a time. While this would not affect the perception of texture, it means that all shapes are perceived as a sequence of touched contours acquired over time. Second, even though the whole fingertip is in contact with the display surface, there is no differentiation of the image within the contact patch. Therefore, if a contoured image has acute angles, the effect of tracing these angles is of a somewhat blurred image beneath the fingertip, with no clear perception of corners or of where the edge of the image boundary is located. Therefore, complex shapes such as the small features found in our Maine coastline example, or indeed the small tactile patterns of Braille, cannot currently be simulated using surface haptic displays. Finally, if the fingertip stops moving, the image beneath the fingertip disappears, further increasing the challenge of contour tracing with a single finger. In terms of EPs, lateral motion is supported, contour following is partially supported, and whole-hand exploration is not supported. In short, such displays may have a role to play in simulating features like soft buttons on flat screens, but they are unlikely to be useful for rendering densely featured tactile images such as our Maine coastline example.

4.1.2 Lateral skin displacement displays

Lateral skin displacement displays are defined here as displays which apply differential stretch to the surface of the skin within the contact patch. As with the surface displays described above, such lateral forces can only be detected if there is relative motion between the fingertip and the surface. Here, parts of the substrate are displaced laterally relative to some underlying uniformly spaced array of elements [32]. As the finger is scanned across the surface, these displaced elements create the illusion of a feature projecting slightly from the flat display surface. Therefore, such displays represent some improvement on surface displays as small features such as individual dots can be rendered beneath the fingertip. Lateral motion and contour following are supported, with some increased resolution of detail within the contact patch. Whole-hand exploration is not supported.

The main disadvantage is that currently the display surface is no larger than the fingertip, meaning that tactile images must be viewed through a tactile portal, analogous to a lens which is moved across a virtual image. Currently, lateral skin displacement displays appear to offer neither the tactile rendering capability of pin arrays (discussed in Sec. 4.1.4) nor the reduction in complexity and hence cost of the surface displays described in Sec. 4.1.1 above.

4.1.3 Vibrotactile displays

While vibrotactile feedback is used with many devices and can be implemented using different techniques, our primary focus here is on those cases where a flat surface, such as the glass or plastic screen of a tablet or smart phone, is caused to move as a unit because it is driven by some form of vibrating source. Typically the source is either an embedded motor or a piezoelectric transducer that can be made to oscillate at frequencies around 250 Hz, as this is the frequency range within which the haptic system is most sensitive to vibration [33]. Typically, when used to render tangible graphics, the surface vibrates when the finger comes into contact with a region of the screen corresponding to a displayed object such as a line in a graph; as long as the screen is capable of only single point detection, the illusion created is that the screen is vibrating only at the point where it is being touched. Here, lateral motion and contour following are both supported to a limited extent, and whole-hand exploration is not possible. Even given these constraints, vibrotactile surface displays have proved to be successful in supporting other modalities to reinforce edge detection for screen objects and for non-visual interaction with graphs and maps [28], [34].

However, there are some important technical and perceptual factors that should be considered when evaluating surface displays using vibrotactile feedback for conveying tangible graphics. In addition to the lower resolution and tracing challenges mentioned in the previous section, the placement and number of motors can make a difference with these displays. If the touchscreen is too large and there is only one embedded vibration actuator, as is the case in most commercial phones and tablets, the signal strength of the single motor degrades across the display extent, making the vibrotactile stimulus hard to perceive or leading to spurious illusions [35].

One notable instance of a vibration display which does support a differentiated image within the contact patch is the Optacon [36]. Here, an array of 6x24 vibrating elements are packed into a surface upon which the index finger rests, while images from a camera held in the other hand are displayed beneath the fingertip. Unlike the vibration displays discussed above that cannot render differentiated images within the contact patch, the vibrating elements within the Optacon's display are independently controlled. Therefore details of the contours of individual letters are easily perceivable beneath the stationary finger. For typical text reading, the Optacon displays only about one letter at a time. Because the elements can be more tightly packed than the pins of, say, a Braille display, the Optacon offers a higher degree of resolution. The main advantage reported for the Optacon is the direct translation of the hardcopy printed image of text into a corresponding tactile image (Optacon is short for "Optical to Tactile CONverter"), as the motion of the camera is directly correlated with the image that appears beneath the finger. But the image is still viewed through a portal, so that the issues relating to exploring with a single finger therefore still apply. Both lateral motion and contour following EPs are supported, with the caveat that, for contour following, tactile and proprioceptive feedback are not co-located because the contour is explored with the hand holding the camera while the result is felt by the index finger on the opposite hand. Lateral motion is also available and can be performed either by moving the camera back and forth over the image or by moving the finger across the display. Whole-hand exploration is not available.

In short, for surface haptic displays that rely on some form of vibrotactile feedback, the effects described can only be felt with one finger, limiting adoption of many of the traditional exploratory strategies for haptic learning and introducing challenges in staying oriented during movement with respect to the global frame of reference of the display [23]. In theory, multi-touch vibration is possible in these devices if individually driven vibrotactile elements could stimulate different fingers based on their precise x-y coordinates on the display, but there is currently no such implementation. As an alternative method to provide parallel processing of vibrotactile information, several groups have affixed external vibrators to the fingertips of two or more digits, thereby allowing more points of contact. Accurate performance was found with this technique for exploration of 2D objects [37], graphs and charts [38], and for accessing maps [39].

Importantly, whereas information about the orientation and thickness of lines, regions, and other graphical elements is directly perceivable from hardcopy tactile output and raised tangible displays (discussed below), accurate extraction of the same information from surface displays (no matter how they are implemented or whether one or more fingers are used) requires integration of touch and kinesthetic cues during exploration. The lack of these explicit cues for detection and guidance of tactual elements may require more cognitive resources using the cues available from surface interfaces than from traditional tactile output [23].

4.1.4 Tactile shape displays (pin arrays)

The most widely available and widely used of all refreshable tactile displays is the Braille display. Braille displays are comprised of an array of individually actuated dots that can be raised above a flat substrate under computer control. Braille is read by running the tips of the index fingers across the display surface. Each Braille character is made up of a subset of six or eight dots (depending on the code being used). While the dots are far enough apart to be individually perceived (for typical 40 character Braille displays the center-to-center spacing is 0.09 inch or 2.29 mm between nearest neighbors in standard English Braille), experienced readers process each character in terms of its overall shape [40].

Unlike the surface displays discussed above, pin array displays allow for a differentiated tactile image within the contact patch. Furthermore, because the dots apply both normal and tangential force to the fingertip as it slides across the display surface, Braille displays preserve both the force and geometry cues of real surface features. Moreover, the whole hand can be placed on the tactile image to gain global shape and layout information. Of all of the surface displays we have discussed, therefore, they represent a tactile experience that most closely resembles its real-world equivalent (reading Braille on an embossed page.)

The primary reason why every blind person who reads Braille does not have a Braille display is cost. An individual, unpackaged Braille cell currently costs approximately $40. When combined to form a display, this cost increases with the purchase price of the integrated array rising to over $2,000 for a single line 16 character unit, and to over $55,000 for a pin-matrix touch tablet composed of 7200 dots [41]. A further limitation is that the cell-based structure of Braille means that regular Braille displays are not easily co-opted for the display of tactile graphics. Ideally a refreshable tactile display would have evenly and densely spaced pins to allow for the rendering of curved lines and angles and would be large enough to display a tactile image such as a line graph. Indeed three commercial products are available that provide dynamic access to tactile graphics. A product called the Graphic Window Professional, (GWP) by Handy Tech, employs several lines of refreshable piezo-electric elements to render images from a computer [42]. The display consists of an array of 24 x 16 pins which move up and down to represent the image. Although the viewing aperture is much smaller than a computer monitor, the user can increase the effective view by panning the image across the display and zooming it in and out to increase or decrease the resolution. A major disadvantage of this product is that the large tactile array makes it very expensive, around $10,000. Moreover, the dot spacing is 3 mm, which is even sparser than the 2.29 mm spacing of the Braille code. This means that the tactile images are somewhat sparse and cannot be used to render curved lines. A similar product from KGS Electronics, called the Dots View DV1, provides a larger tactile viewable aperture consisting of a 32 by 48 dots dynamic display matrix and costs roughly $16,000. This unit employs a denser array of dots, with the 2.4 uniform dot spacing leading to a perceptible increase in resolution. The third commerically available dense pin array is the HyperBraille, from Metec [41]. This display is comprised of a matrix of 7200 dots arranged in a 60-by-120 array with an inter-dot spacing of 2.5 mm and driven by vertical piezo reeds. The display is also touch-sensitive, allowing for co-located input and output, for example to rout the cursor to the reading point. While the HyperBraille is the most advanced tactile graphics display currently available, its cost (approximately $56,000 at the time of writing) puts it beyond the reach of individual blind computer users.

There have been many attempts to build low-cost Braille displays. The most common approach is to assume that, because the fingertips only encounter one or two Braille characters at a time in normal reading, one could build a display using only one or two Braille cells and allow the user to move a cursor across a virtual page, displaying characters or tactile graphics, as the cursor passes over them. Indeed some such devices even made it to market, e.g. Virtouch (described in [43]), but were ultimately commercial failures because blind users found them difficult to use. These displays failed for two possible reasons. First, the tactile image is refreshed beneath the fingertip when the dots move normal to its surface, retaining geometric shape cues but removing the tangential force cues created in Braille reading when the finger slides across a line of text. As Folke and others have shown, both normal and tangential cues are necessary for the most efficient pick-up of information through the tactile reading of Braille [44]. Second, users found it difficult to trace the paths of lines on the visual image, so that edge detection and contour following were greatly impeded.

Cost aside, large pin-based tactile displays are by far the most suitable haptic technology for displaying Braille and for rendering graphic images whose shape is to be explored by one or both hands. If their underlying actuator technology could be redesigned to accommodate appropriate spacing for tactile graphics and if their cost could be reduced dramatically, they could be used for non-text applications as well. However, their ability to resolve small features within an image, (e.g. of our Maine coastline), will always be limited by inter-dot spacing. While there are, as of now, no quantitative measures available for the optimal pin spacing for refreshable displays for rendering tactile graphics, work by one of the authors on developing tactile embossers indicates that an inter-dot spacing of 10DPI can be used to render straight lines that appear to be continuous and curves that are not ideal but are smooth enough to be useful. A display with greater resolution is always going to be better, up to some point; where that point lies precisely is still an open question.

4.1.5 Bubble displays

An emerging form of surface display to be considered here are so-called ’bubble’ displays. Here, small cavities beneath a flexible surface can be selectively inflated to create tangible surface features such as bumps and edges. While this technology is in its infancy, it holds some potential for the display of tangible text and graphics. First, such displays are likely to cost less when compared to pin arrays because there are few moving parts to be assembled and maintained and because this technology is being developed for uses far beyond rendering Braille or tactile graphics, that is for creating so-called ’soft’ buttons for flat screens on tablets and phones [45]. As with tactile pin arrays, these displays support exploration using our three key EPs. A current limitation of this approach is that the features that can be displayed are fixed, that is their location, size and shape is determined by the shape of the cavities below the surface. An approach currently being developed by one of the authors goes some way to address this issue in that bubbles are not directly felt by the reader, but are used to drive pins to create dots of a size, height and spacing appropriate for Braille [46].

4.1.6 Force displays

Force displays such as the PhanToM [47] depart somewhat from the surface displays discussed above in that the surfaces they render are virtual surfaces. As such, the density of the features they can render is not limited by any physical constraint such as the packing density of actuators. A limitation of such displays for rendering tangible images is that they typically provide only a single point of contact with the surface being rendered. Moreover, this contact is not direct, but is mediated by the device's end-effector (e.g. a pen in the case of a PhanToM, or a ball-like handle as in the case of the Falcon).

As noted earlier, such limited interaction forces the user to employ unusual strategies for piecing together the elements of an image. While it is still possible to determine aspects such as the contour of our Maine coastline example using a single point, it is not an optimal strategy as the impression of the surface acquired as a series of displacements of the hand over time has to be integrated in the user's mind to build up a spatial representation of the image [48]. Lateral motion is also supported but whole hand interaction is not (except in the case of a device such as the cyberglove [49], where forces can be applied to all five fingers and the impression of whole hand interaction with an object can be created.

These issues aside, virtual haptic displays have the potential to provide a means of rapidly rendering simple line graphs and, when supplemented with speech, can be an effective means of conveying quantitative information to blind users (e.g. [50]). A further advantage of many force feedback displays is that they can render objects in three dimensions and can therefore provide topographic information for maps, for example for orientation and route training applications. Magnussen and Rassmus-Grohn, for example, designed a 3D rendering of a complex street crossing in Lund, complete with moving cars, to acquaint blind pedestrians with the layout of the intersection and the traffic light cycle [51].

Because haptic displays can render both static and dynamic effects, they offer much potential for providing access for blind users to dynamic simulations such as required for math and science applications. Even static forces can serve to convey information about dynamical systems if used to simulate an interactive model. For example, Wies et al. used changes in both the direction and magnitude of forces to simulate the behavior of an electric charge on the surface of a simulated sphere [52]. Finally, because force displays can simulate both static and dynamic effects, it is possible to overlay static renderings of object surfaces with motion or vibration. This layering can be used, for example, to indicate a change in status of an object if a button is pressed, a line segment is selected, and so on.

In summary, force displays have the potential to provide an effective means of rendering surfaces and objects to be touched. Their advantage is that some can render in 3D and that both static and dynamic effects can be combined. Their primary disadvantage is that they are single-point-of-contact displays, requiring users with no access to visual feedback (e.g. 2-D or 3-D visual renderings of the haptic objects), to integrate object contours over time. Further, there is a patchy history of access to commercially available low-cost haptic devices, a fact which further limits their usefulness for adoption by a wide population of blind computer users.

4.2 Multimodal technologies

The advantage of refreshable touch displays compared to other non-visual interfaces (e.g., verbal or auditory displays), is that they provide direct perceptual access to spatial information. For instance, although rendering an exact replica of Maine's coastline may not be possible through touch, it is far easier to generate and interpret this information through tactual output than trying to render it using only spatial language or spatial audio (but see [54] for an example of how audio-kinesthetic feedback was used for conveying spatial layout while exploring a touchscreen). In contrast, non-spatial information or other cues such as names and other semantically-rich information is often easiest and most intuitive to convey via speech and can easily be implemented to complement haptic information. This means that we can carefully constrain and down sample only the most critical information for the task, and we can optimize the interface to present this information through multimodal cuing. For instance, spatial information about graphical material can be presented through vibrotactile cues and kinesthetic feedback, and semantic information through auditory labels. This approach ensures that a non-visual display is both matched to the information processing strengths and limitations of the end-user, while also being optimized to support the key tasks of interest. The advantages of using multimodal haptic/tactile plus audio displays for accessing graphical information are well known ([53], [50]) but the proliferation of new electronic displays over the past few years has opened the door to developing multimodal interfaces of all kinds. These may include using a touch screen with audio-kinesthetic input and audio output for representing complex indoor layouts [54], accessing graphs [55], and other general informational graphics. Some displays also add vibrotactile or electrostatic output, such as the vibro-audio interface for accessing graphs and maps ([28], [56]) or the electrostatic TeslaTouch display [30].

An advantage of multimodal interfaces is that they can be implemented as part of a haptic/audio multimodal display on commercially available hardware, such as smartphones and tablets. By all accounts, this is the fastest growing computing platform used by blind and visually impaired people, which makes good sense as these devices provide dynamically-updated information, are multipurpose (meaning that they replace many separate and expensive pieces of access technology) and include a myriad of built-in universal design parameters (e.g., speech input/output, magnification, high contrast, and vibration). Whatever the specific technology may be, it makes sense for future refreshable touch displays to build on this multimodal, multi-use model of graphical access.

5 CONCLUSIONS

As we have discussed in this paper, there is an immediate need for research and development of new technologies to provide non-visual access to graphical material. While the importance of this access is obvious in many educational, vocational, and social contexts for visually impaired people, the diversity of the user group, range of available technologies, and breadth of tasks to be supported complicate the research and development process. Designers must be cautious, take care to match the technical solution to the user requirements, and realize from the onset that this match will be different depending on different tasks, different users, and different technologies.

In line with recommended practice for user-centered design, designers should first consider the demographic characteristics of the target population for which the display is intended. Section 2 provides insight into the range of blind and visually impaired users who should be considered when designing tangible displays.

Another important aspect of designing tangible technologies involves consideration of the sensory and perceptual characteristics of touch and the inherent differences that exist between vision and touch. As we described in Section 3, in the vast majority of instances, simply converting a visual image into tangible form, no matter the rendering technology used, will lead to a confusing and meaningless output. Care must be taken to consider what information should be conveyed and how principled simplification and schematization rules can be used to improve legibility. As was discussed in Section 4, the extent to which any category of technology supports perceptual constraints, exploratory strategies, and redundant cues is highly variable. The bottom line is that there is likely to be no single approach that will solve the graphics access problem. However, three rules of thumb that are broadly applicable include:

1) adopting a less is more design philosophy; this is the best way to ensure that a tangible display will be both meaningful and usable.
2) taking into consideration the capabilities of the perceptual systems for which the media will be designed; this requires consideration of how information should be distributed across modalities and how efficiently it can be picked up even within a given modality.
3) supporting multimodal information in the interface; this is the best way to reach more users, via the most intuitive information delivery, for supporting the widest array of tasks.

Designers should understand the critical nature of starting a project with the first step: considering the pros and cons of each display option. For instance, some displays, (e.g., pin displays), are closer to traditional tactile hard copy renderings and afford use of multiple fingers during exploration but are very expensive. Others, such as the various surface displays, are less expensive and increasingly commercially available as part of multimodal interfaces (e.g., smartphones) but suffer from allowing only single-digit exploration and supporting only a limited number of the most important exploratory strategies. If dynamic rendering of three dimensions is necessary, force feedback displays (and perhaps the bubble displays of the future) are the most appropriate options but these systems are not readily available and are not natively multimodal. While designers may initially strive for a "one-size-fits-all" approach to the design of access technology, we hope that understanding the trade-offs between the technologies that we have described illustrates the problems inherent in this approach. By highlighting some of the key pitfalls leading to this engineering trap, enumerating the type of exploratory strategies that are best suited for multiple categories of technology and drawing attention to the challenges of conveying information through touch, we hope that this paper provides some guidance on technology development and usage that will narrow the information gap for visually impaired users. Although we have not provided a formal set of design guidelines, we have provided some much needed discussion of the foundational principles and key issues that should be considered and from which we hope more elaborated design principles might emerge.

Finally, we note that understanding tactile graphics is not an automatic skill. It takes practice for blind people to learn to comprehend tactile information easily. Since few blind people have the opportunity to learn the necessary skills, they often have trouble understanding even relatively simple tactile graphics without practice. Multimodal haptic/audio interfaces are far more effective for most people [57]. Protocols for evaluating the functionality of tactile displays should take into account the likely need for training or practice by potential users.

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