Designing Haptic Assistive Technology for Individuals Who Are Blind or Visually Impaired

Dianne T.V. Pawluk, *Member, IEEE*, Richard J. Adams, *Senior Member, IEEE*, and Ryo Kitada

Abstract—This paper considers issues relevant for the design and use of haptic technology for assistive devices for individuals who are blind or visually impaired in some of the major areas of importance: Braille reading, tactile graphics, orientation and mobility. We show that there is a wealth of behavioral research that is highly applicable to assistive technology design. In a few cases, conclusions from behavioral experiments have been directly applied to design with positive results. Differences in brain organization and performance capabilities between individuals who are "early blind" and "late blind" from using the same tactile/haptic accommodations, such as the use of Braille, suggest the importance of training and assessing these groups individually. Practical restrictions on device design, such as performance limitations of the technology and cost, raise questions as to which aspects of these restrictions are truly important to overcome to achieve high performance. In general, this raises the question of what it means to provide functional equivalence as opposed to sensory equivalence.

Index Terms—Blindness, visually impaired, haptic displays for the visually impaired, assistive technology for the visually impaired

◆

1 INTRODUCTION

In developing assistive technology for individuals who are blind or visually impaired (BVI), among the most important considerations are the characteristics of the target population and their interactions with the environment. Improper consideration of these characteristics has, in part, resulted in numerous assistive technology research projects failing to transition to real-world use. In this review of the application of haptics to this subject, we consider the following key elements: the characteristics of the population and their involvement in the design process; current understanding of the behavioral research in key areas; some example insights from behavioral research that were applied to the design of assistive technology; and some examples of relevant assistive technology that has been developed for key tasks. The four task areas which will be the focus of this paper are: Braille reading, tactile graphics, orientation and mobility. A paper by O'Modhrain and her colleagues (in this issue) provides a valuable perspective by experts in the field who also happen to be BVI.

2 DESIGN

In designing assistive technology for individuals who are BVI, many different areas of knowledge should be considered. In this section, we describe issues involving the target population characteristics in terms of the diversity of the target population and some basic issues in sensory substitution. We also describe aspects of the design process particular to assistive technology: the use of participatory action design and the importance of testing devices in the real-world.

2.1 Diversity of Population

One of the most important aspects to appreciate in designing assistive technology for individuals who are BVI is the diversity of the population in terms of medical condition, experience, opinions, preferences and motivation. Vision impairments range from low vision through light detection only to no vision at all [1]. The parts of the eye affected may also vary; however, this is mainly associated with low vision and of more importance when considering visual enhancement rather than haptic displays. An individual may also have other impairments which could affect design decisions. For example, deaf-blind individuals may also vary in their degree of hearing, which may result in the need for an exclusively haptic (versus audio-haptic) solution [2]. However, a frequent cause of blindness is diabetes that can also produce neuropathy in the peripheral extremities resulting in a lack of sensitivity in the fingertips and toes [3]. These individuals may require a solution that, at the very least, requires the provision of haptic feedback closer to the central core of the body (e.g., wrist or torso). Finally, individuals may also have cognitive impairments which, together with issues of information transmission bandwidth (see Section 2.2), can have an impact on design decisions.

Individuals may also vary greatly in terms of their experience, preferences, opinions and motivation. In terms of visual experience, the population can be categorized into those who are congenitally or early blind, and those who are adventitiously or late blind. The primary differentiator between these two populations is whether the individual has had visual experience before becoming blind. Potential key milestones that may lead to later differences are: (1) by eighteen months, infants have experience with reaching and

---

- *D.T.V. Pawluk is with the Biomedical Engineering Department, Virginia Commonwealth University, Richmond, VA 23284. E-mail: dtpawluk@vcu.edu.*
- *R.J. Adams is with Barron Associates, Inc., Charlottesville, VA 22901. E-mail: adams@barron-associates.com.*
- *R. Kitada is with the National Institute for Physiological Sciences, Okazaki, Japan. E-mail: kitada@nips.ac.jp.*

Manuscript received 15 June 2015; revised 16 Aug. 2015; accepted 18 Aug. 2015. Date of publication 26 Aug. 2015; date of current version 14 Sept. 2015. Recommended for acceptance by L. Jones.
For information on obtaining reprints of this article, please send e-mail to: reprints@ieee.org, and reference the Digital Object Identifier below.
Digital Object Identifier no. 10.1109/TOH.2015.2471300

1939-1412 © 2015 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission.
See http://www.ieee.org/publications_standards/publications/rights/index.html for more information.

moving in the environment with vision, and (2) at a somewhat later age, they often have experience with visual graphics (including perspective) and text words [4]. Many studies in the behavioral literature have shown differences between these two groups (see Section 3). Neuroimaging studies (e.g., [5]) suggest that there are differences in brain organization between these two groups. It is also important to differentiate these populations from sighted individuals who are blindfolded, who may have very different performance and brain organization.

Other important experiences that can affect the use of haptic/tactile assistive technology include an individual's familiarity with and acceptance of technology, as well as experience with touch. Regarding the first issue, the target population is often divided between the elderly and the young [6] due to the disparity between age groups when it comes to familiarity with various technologies in general. For the second issue, those individuals who have experience exploring with touch may perform better with assistive technology using touch than those that do not. For example, neuroimaging studies have shown an expansion in the cortical area representing the reading finger in extensive Braille users [7]. However, it should be noted in regards to designing assistive technology that only 10 percent of individuals who are visually impaired are Braille readers [8].

Motivation, preferences and opinions also can have a great impact on the acceptance of assistive technology by users and user performance, although their effects have been less studied than medical condition and experience. One example of the effect of motivation on performance was studied in an indoor way finding task [9]. In the task, participants who were motivated with a monetary incentive to complete the task as fast as possible performed significantly faster than the control group without an increase in errors. Individual preferences can be designed into programmable technology through user settings. Providing a choice is desirable but, as with any good user interface, should be restricted and have a default setting to avoid overwhelming the user. It should also not be used as a substitute for behavioral testing to determine what sensory parameters can lead to high performance.

Sometimes differences of opinions among individuals who are BVI may make it difficult for a designer to make design decisions that accommodate all individuals. For example, audible pedestrian signs, which provide an audible tone to indicate it is safe to cross the street, have both strong advocates and strong opposition [10]. The difference in opinion seems dependent on whether the audible signage will be the only information used by individuals to cross the street or whether they will use the sounds of the cars present to make judgments as well. One consistent opinion of many individuals who are BVI that we have interacted with in focus groups is that there is a strong reluctance to become critically dependent on a piece of technology that may be slow and costly to repair or replace.

2.2 Some Background on Tactile/Haptic Sensory Substitution

One of the earliest considerations of haptics for sensory substitution is the pioneering work of Bach-y-Rita and his colleagues on reading, picture recognition and mobility [11]. For their system, the user manipulated a television camera to view objects. A subsampled tactile "image" was then presented on a 20 × 20 grid of vibrating solenoids spaced 12 mm apart on the back of a dentist's chair that the user sat in. Subsequent work has used arrays on the abdomen, back, thigh, forehead and fingertip, as well as electrotactile displays [12]. One interesting aspect of their results is that when the camera system was controlled by the user, users reported experiencing images in space, rather than on the skin. This was not reported if the user did not actively control the camera, suggesting the importance of active exploration in the formation of this attribution. Individuals were also able to make perceptual judgments using visual means of interpretation such as perspective, parallax and zooming. Although this technology did allow well-trained individuals to gain a degree of knowledge about simple static scenes, the dynamic and complex nature of real-world environments limited its applicability [13].

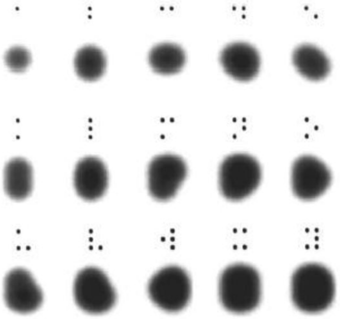

Fig. 1. The Braille characters are visually blurred (as seen below each character) to a degree that produces the same level of recognition as for touch (from [14]).

2.2.1 *Tactile (Mechanical)*

One issue in using touch as sensory substitution for vision is the significantly limited spatial resolution of touch (Fig. 1) as compared to vision due to the low-pass filtering of the cutaneous system [14]. The spatial resolution also depends on the temporal frequency of the stimulation [15] and body site. On the fingertip, spatial acuity appears best for temporal sinusoidal stimuli in the frequency bands of 1-3 Hz and 18-32 Hz, as well as showing a decreasing trend with increasing frequency over 50 Hz [15]. Spatial acuity is also different for different body sites. For example, the resolution for nonvibrating stimuli is approximately 1.0 mm on the fingertips [16] and 40.0 mm on the back [17]. These numbers can be compared to visual acuity which is approximately 0.15 mm when looking at an image from a distance of 0.5 m.

Several studies have also found that the spatial resolution on the fingertips of individuals who are early blind and Braille readers is significantly better than that of sighted individuals (e.g., in [18], 1.04 mm compared to 1.46 mm). However, evidence suggests that this difference is due to tactile experience [19] and is eliminated if both groups are given practice [20].

Another issue is that the field of view (FOV) for vision is considerably larger than that of touch. Most research has examined this issue using raised line drawings explored by the fingers (see Fig. 2, on left) and found that the FOV does not really extend beyond a single finger (e.g., [21]). A

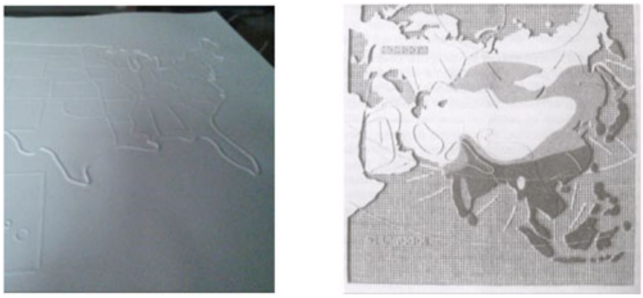

Fig. 2. On the left is a typical raised line drawing. On the right is a typical hand-made drawing (from [48]).

modest improvement in performance was found when five fingers were used, although this may have been due to reasons other than an increased perceptual FOV [22]. In addition, the FOV may increase when material properties are involved (see Section 4.1). The importance of the size of the FOV is that it eases top-down processing by providing spatial context, which can greatly aid in perceptual organization and object recognition. For touch, with diagrams larger than a single finger, information must be pieced together serially and retained in memory (which is both memory intensive and time consuming) to allow top-down processing.

Although we are not aware of any studies examining the FOV of other body sites, the back and the abdomen have generally been treated successfully as continuous surfaces. However, as the spatial resolution is more limited on these body sites than on the fingers, the larger FOV does not imply that a larger amount of spatial information can be conveyed on these sites compared to the fingers.

Other important considerations for sensory substitution are behavioral similarities and differences between the visual and haptic sensory systems (see Section 3), as well as consideration of the neuroplasticity of the brain.

2.2.2 Electrotactile

Electrotactile displays are a possible alternative to haptic displays providing mechanical stimulation. The intention of these displays is to stimulate the nerve fibers of the mechanoreceptors directly. Their advantage is that they are significantly more compact, easier to fabricate and have lower power consumption. However, the haptic sensations generated have not been studied as thoroughly as mechanical stimulation. The sensations produced have been described by subjects as feeling a vibration, light buzzing or pulsing, although with a “slightly electrical nature” [23]. One potential limitation of electrotactile stimulation is that it is difficult to stimulate the deeper receptors (the Pacinian Corpuscles) that produce the response of the tactile system at higher frequencies [24]. In addition, changes in perception can occur due to variations in electrical impedance of the skin and subcutaneous tissue over time, such as through sweating.

As with the spatial acuity of mechanical stimulation, the acuity of electrical stimulation applied to the surface of the skin is expected to be affected by both neural properties and properties of the skin and subcutaneous tissue. Research results suggest that the spatial acuity of the tactile system to electrical stimulation is in the range of 5-10 mm on the back, compared to 40.0 mm for mechanical stimulation [25]. On the tongue, spatial discrimination of electrical stimulation is in the range of 1.6–2.7 mm [26] as compared to 0.5 mm for mechanical stimulation [16]. However, the spatial discrimination methods used on the tongue were different for the different stimulation types and it is possible that the acuity may be more comparable between the two. No studies have examined the FOV, although we would expect the FOV to be the same for the two types of stimulation.

Although our focus in Section 5, describing current haptic assistive technology for individuals who are BVI, is on systems providing mechanical stimulation, assistive technology displays have been developed that provide electrical stimulation to the fingertip, back, abdomen, tongue and forehead (e.g., [27], [28]). The search for the optimal target location on the human body for electrotactile stimuli to achieve sensory replacement has led to a seemingly unlikely destination—the tongue. The advantage of using the tongue is that it is an environment relatively constant and low in electrical impedance due to its thin cutaneous layer and continuous saliva bath [29].

Bach-y-Rita and his colleagues, in their pioneering work, also investigated the use of electrotactile displays. One of the first assistive technology systems they developed employed a 12 × 12 Cartesian grid of electrodes on the tongue with 2.34 mm center to center spacing to display images acquired by a head-mounted camera [28]. The system is currently being commercialized as the BrainPort by Wicab, Inc. (Middleton, WI). The BrainPort V100 has a 400-element electrode array that connects to a pair of glasses that also supports a small camera. The grayscale images from the camera are mapped onto the display and are rendered such that white pixels result in higher levels of electrotactile stimulation while black results in no stimulation [30].

2.3 Participatory Action Design

User centered design practices are now quite commonplace in the development of products. The process includes: determination of users’ needs through focus groups, ethnography studies, preference surveys, attribute experiments and other data gathering methods [31]; the consideration of universal design issues [32]; and usability of prototypes and the final product (e.g., [33], [34]). Participatory Action Design takes user centered design a step further by involving stakeholders throughout the design process [35]. This may include users, care providers, and other stakeholder participation in activities such as storyboarding, low technology prototyping and real-world testing of end products.

2.4 Real-World versus Laboratory Testing

Assessing the performance of assistive technology in real-world environments rather than in isolated laboratory testing is also an important step towards the successful development of usable technology. One reason is that real world environments (such as navigating busy streets) are expected to be noisier and more distracting than laboratory environments. Alternately technology, such as headphones covering the ears, may provide undesirable isolation in a real world environment affecting safety or social interaction.

Additionally, multiple tasks often need to be performed at the same time in the real world. For example going from one location to another can involve both obstacle avoidance and navigation technology. This creates two potential differences from laboratory testing. First, there are less attentional resources available than when considering one of these tasks in isolation in the laboratory. Second, multiple devices may need to be carried and used at the same time for the different tasks in addition to items for day-to-day use such as briefcases, knapsacks or shopping bags. Even in an office environment, a user may need to switch between the use of Braille and tactile graphics frequently, influencing the design of both.

Finally, wearable technology which cannot easily be removed or turned off by the user may be tolerable in short term test environments but not as much in everyday environments. This is in contrast to non-wearable visual or haptic technology, where the user knows they can easily look away/close their eyes or remove their hand from a display if they do not want to experience the feedback.

3 BEHAVIORAL AND NEUROIMAGING RESEARCH

Behavioral research is very important for the development of useful assistive devices by objectively describing differences and similarities between the visual and haptic systems, which can be used to guide the transformation of information from one domain to the other. Understanding differences in perceptual processing between congenitally blind, late blind and sighted individuals is also important in addressing the controversial issue of using sighted individuals for part of the testing and introspection, either consciously or unconsciously, by sighted designers. Furthermore, neuroimaging research highlights the plasticity of the somatosensory cortex with training, which is useful to consider in technology use. In addition, it also reveals fundamental differences in cortical organization between congenitally blind, late blind and sighted individuals, particularly in regards to the use of the visual cortex (e.g., [36]).

This section focuses on haptic behavioral research and imaging studies related to the four areas of assistive technology this review paper considers: Braille displays, tactile graphics displays, orientation and mobility. Here we review research on the use of Braille, tactile graphics and haptic locomotor spatial perception by individuals who are BVI. In addition, we consider the relatively new area of affective touch and its potential utility to assistive technology design.

3.1 Braille

In Braille, each letter is represented by a configuration of dots within a 3 × 2 dot cell, with dots spaced approximately 2.3 mm apart [37]. Although by sight each Braille character is typically distinguished by its explicit dot pattern within a cell, this is not true for tactual reading (Fig. 1), which is often described as being perceptually determined by "overall shape" (or, more specifically, the lower frequency content, which are the only frequencies retained tactually). Evidence suggests that Braille's tactual effectiveness compared to embossed alphabet letters is due to its greater distinctiveness between characters within this lower frequency band [38].

3.1.1 Reading Method

Reading Braille can be performed with one or two hands, scanning from left to right, typically using only the index finger(s), and with regressions to move the finger(s) over previously covered material to help disambiguate content [39]. The use of two hands is known to be superior in speed to the use of one: the movement pattern typically starts with the left hand scanning a line, taken over by the right hand, with the left hand then simultaneously looking for the next line [40], [41]. There are two possible interpretations of the hand movements: (1) the left only finds the beginning of the new line, but does not read it, while the right finishes reading a line [41], or (2) both hands read text simultaneously [40]. However, Bertelson et al. [40] showed that reading was faster the less two hands were on the page together, suggesting the first interpretation. This distinction is important as there may be cheap one-handed refreshable Braille solutions that include an alternate method to find a new line but are unable to substitute for reading with two hands simultaneously.

For touch in general, active touch (i.e., the purposeful exploration of the stimulus) is regarded as superior to passive touch (where the stimulus is either statically applied or scanned across the hand). Heller found, at least for naïve sighted participants, that active touch for Braille reading was significantly superior to passive movement across the finger, and both were greatly superior to passive static contact [42]. Recent work by Russomanno and his colleagues (in this issue), with individuals who are BVI, found that both the proprioceptive information from the hand moving from character to character and tactile information on sliding contact between the fingertip and Braille character are important for effective reading.

3.1.2 Neuroimaging Studies

Neuroimaging studies have shown that the neural substrates underlying haptic Braille reading critically differ between individuals who are early blind and those who are sighted. For instance, Sadato et al. [43] found that for early blind subjects proficient in Braille, Braille reading and tactile discrimination tasks (including reading embossed English letters) elicit activation in the medial occipital lobe corresponding to the primary visual cortex (V1) as compared to the rest condition where the subject is relaxed and not conducting any task. However, for sighted subjects, the same region showed a decrease of activation (relative to the rest condition) during the tactile discrimination tasks; no Braille reading was performed presumably because the sighted did not know Braille.

Further support that the early visual cortex is involved in Braille reading by the early blind comes from work with transcranial magnetic stimulation (TMS) applied to the occipital (visual) cortex while performing reading tasks [44]. As compared to TMS in the air, TMS on the occipital cortex increased the error rate in both Braille identification and embossed Roman letter identification by early blind subjects but not in embossed Roman letter identification by sighted subjects. Additional support for the role of the primary visual cortex comes from the anecdote of a proficient Braille reader blind from birth. Upon sustaining bilateral occipital damage from an ischemic stroke, she was no longer able to read Braille [45].

There have been few imaging studies comparing Braille reading with early and late blind individuals. One informative and relevant study [36] compared cortical activation during a tactile discrimination task. They found that the primary visual cortex increased its activation (from rest) during a tactile discrimination task for subjects who lost their sight before 16 years old, but decreased activation (from rest) for those who lost their sight after 16 years old. This suggests that the massive plastic change in the primary visual cortex occurs when individuals become totally blind in their young age.

These differences between early, late and sighted individuals may explain why the early blind outperform the other groups in terms of their efficiency in Braille reading [46]. However, it is still unclear whether the absence of early visual experience alone explains the reorganization of the visual cortex for Braille reading. It is reported that the representation of the reading fingers in the primary somatosensory cortex is enlarged for the early blind as compared to the other groups (e.g., [47]). By analogy, it is possible that the experience of extensive tactile learning may explain such reorganization in the visual cortex as well [7].

3.2 Tactile Graphics

A variety of different methods are used to create physical tactile graphics, all producing different types of diagrams [48]. The most commonly used methods are: hand-made tactile pictures, embossed diagrams, the use of microcapsule paper and vacuum forming. Hand-made tactile pictures (Fig. 2, right) that use textured cloth and paper, string, wood, metals and other materials are the most frequently used method with young children due to their effectiveness. Embossed displays can be made by hand or, more typically, using modified Braille embossers. Modified Braille embossers “punch” raised dots in thicker, specialized paper, with a typical resolution of 20 dots per inch. Microcapsule paper is a specially coated paper that will expand in areas coated with black ink when exposed to heat. An ink printer is usually used to print the black image on the paper. An effective set of textures can be created for microcapsule paper, although the expansion process may not be uniform in some cases. Vacuum-forming is used when more than one copy of a tactile diagram is needed. A built-up master tactile diagram is formed using a variety of materials. The copies are formed by heating plastic over the master with a special machine. The relief amplitude is not restricted to one level and textures can be created.

All of these methods can be both expensive and time consuming, and hence, with the increased use of graphics to convey information in society, there is a need for effective refreshable display solutions. However, there are several limitations with physical tactile diagrams which, if understood, may lead to more effective display solutions.

3.2.1 Raised Line Drawings

Raised line drawings are simple line drawings of objects, object scenes or graphs for which the lines are raised up from the background surface (Fig. 2, left). Unfortunately, the identification of even common objects is very poor when using raised line drawings, with an average accuracy between 10-40 percent and a response time up to minutes to explore a diagram, even with both hands [21]. This is likely due to the limited field of view of touch (see Section 2.2) which results in the need for significant serial processing (which is slow and cognitively demanding) and limits top-down processing (which aids in disambiguating lines of shape from perspective and occlusion lines).

However, the above results were obtained with no context for the diagrams. Typically tactile diagrams will come with titles, labels and, possibly, an associated text paragraph. In [49], category information was used to provide context. With this context provided, participants greatly improved their accuracy and speed of picture identification. Unfortunately there are also likely to be many cases where the context is limited and/or difficult to comprehend without familiarity with the material.

There also seems to be differences in performance between sighted, early blind and late blind individuals when using tactile graphics. Late blind individuals seem to perform the best, with sighted and congenitally blind having similar average performance [50]. Heller attributed these results to two factors: (1) the experience of late blind and sighted individuals with pictures (due to visual exposure) is greater than for early blind individuals; and (2) the tactile skills of the late and early blind are greater than the sighted. This is also consistent with results by Lederman and her colleagues comparing sighted to early blind individuals [51] as well as more recent work by Heller et al. [52]. In addition, the latter work showed that individuals with very low vision performed as well as individuals who are late blind.

3.2.2 Textured Diagrams

Although, raised line drawings have almost exclusively been used in studying the perception of tactile graphics, in practice hand-made drawings using textures, string and other materials (Fig. 2, right) are strongly preferred due to their greater effectiveness. Objective comparisons between using textured and raised line diagrams are considered in Section 4.1 for hand-made [53] and mechanical display methods [54].

3.2.3 Increasing Effectiveness

Several researchers have considered different ways to potentially improve performance with raised line diagrams. Recently, Wijintjes et al. [55] found that recognition of raised line drawings was modestly improved when picture size was increased. This is consistent with practices by teachers for the blind and visually impaired (TVIs) for which areas with small details are scaled up and presented on a separate sheet of paper to improve recognition. However, this is usually performed by TVIs when the details are small, in contrast to the previous study, where it appears that increasing picture size even when details are perceptible improves performance. Simplification is also an important process TVIs use to make a diagram more accessible. Simplification usually refers to removing “clutter”, that is to say, unneeded details. Another important aspect is deciding whether shapes can be simplified in the diagram for easier interpretation.

3.2.4 Perspective

TVIs who develop tactile diagrams for students will normally remove perspective from a picture to help with comprehension. This removes one difficulty in trying to interpret whether lines on a drawing are depicting object shape or some other aspect of the diagram. Frequently individuals who are BVI will describe objects in 3D (rather than 2D), including drawing a "folded out" version of the object depicted [48]. However, spatial relationships described by perspective are an important part of scholastic testing and, therefore, their effective representation is a significant concern for TVIs and their charges.

Perspective in 2D diagrams is currently very difficult for individuals who are BVI to understand, which puts them at a disadvantage relative to their sighted cohort. However, work by Heller et al. [56] suggests that visual experience, as argued by others, is not necessary for understanding perspective, while exposure to the rules of perspective is. This suggests that perhaps with a better notation for indicating perspective that is less easily confused with other aspects of the diagram and with training, BVI individuals will be able to improve their comprehension skills for 2D pictures.

3.2.5 Neuroimaging Studies

Several neuroimaging studies have revealed that the haptic recognition of 3D common objects involves a distributed network of brain regions beyond the somatosensory cortices in both blind and sighted individuals (e.g., [57]). Activation of regions in and around the primary visual cortex is also frequently observed in individuals who are blind ([57]). In contrast, to the best of our knowledge, no study has explicitly reported the brain network of blind individuals involved in haptic recognition of 2D raised-line drawing (as in Fig. 2). Except for the difficulty in tactually perceiving 2D graphics, we expect that the haptic processing of 2D and 3D objects involves the same cognitive components such as representing spatial properties (e.g., shape and orientation) in spatial reference frames (see Section 3.3) and retrieving the associated information from memory (e.g., name) to identify it. Therefore, it is reasonable to predict that haptic processing of spatial properties of 2D and 3D objects share common brain networks. It is still unclear how the involvement of the primary visual cortex contributes to the performance of haptic object recognition by individuals who are blind.

3.3 Haptic Locomotor Space Perception

Spatial perception can refer to a wide range of perceptual activities (e.g., [58]). Here we will focus on activities related to the important application areas of orientation and mobility such as described in the review by Long and Giudice [59]. In addition, although audition plays important roles in the spatial perception of noise emitting objects out of reach and in echolocation, it is beyond the scope of this paper. The focus here will be on haptics only.

3.3.1 Frames of Reference

There are two general frames of reference considered in spatial perception. The first is an egocentric frame of reference, where objects are referred to with respect to the location of the self. The second is an allocentric frame of reference, where the reference frame is external and references objects directly to one another [59]. In egocentric frameworks, route descriptions are used which have a sequential organization and for which relative spatial information is conveyed by relationships such as "to the left" or "to the right". In contrast, in allocentric frameworks, survey descriptions are used which are often hierarchical and for which objects are related in terms of "north", "south", "east" or "west" [60].

In sighted individuals, tactile stimuli in the environment are perceived in an egocentric frame and are usually then remapped into an allocentric frame through the modulation of visual inputs. As this mapping also appears to be performed to a comparable degree by individuals who are late blind, the requirement seems to be one of previous exposure to vision rather than currently possessing vision. Individuals who are congenitally blind do not have this exposure and are more likely to use proximal, egocentric information (e.g., [61]). Consequentially, they are likely to represent information about a path in route-like rather than survey-like form [62].

3.3.2 Performance

The ability to maintain a stable body reference in egocentric tasks benefits performance in small spaces where objects are within reach (i.e., manual tasks) [63]. For locomotor space, when examining simple, primarily egocentric tasks such as simple distance and angle estimation, retracing a route, angle completion, finding the closest point of interest (POI) to the home position and pointing from the home position to a POI in a relatively small and open environment (i.e., a room or a parking lot), similar performance seems to occur for early blind, late blind and blindfolded sighted participants [64], [63].

When considering more allocentric related tasks, more varied results have been obtained, although in general individuals who were early blind appeared to have more difficulty than those who were late blind or sighted and blindfolded. Individuals who were late blind actually appeared to do better than the two other groups on a task imagining the closest POI to a non-home position, although those who were sighted were much faster than the others [63]. For imagining pointing to a POI from the location, the condition of blindness did not have an effect on performance [64], [65]. However, the performance of participants who were sighted or late blind greatly improved if they physically walked to the pointing location [65]. Individuals who were early blind also performed more poorly and took longer to do tasks involving new route formation or estimating straight line distances [66]. Finally, although the mental spatial relationships of individuals who were congenitally blind appeared to maintain the metric structure of the real world, the representation was poorer than that of sighted individuals [67].

3.3.3 Cognitive Maps

Cognitive maps are mental representations of a spatial layout in a person's head and which may include distortions, holes and other exaggerations of the real world [59]. Although individuals who are congenitally blind generally use an egocentric representation when walking a path, it appears that using a tactile map can facilitate their development of an allocentric cognitive map (Fig. 3, left). This is supported by the results in [68] which suggest that there is

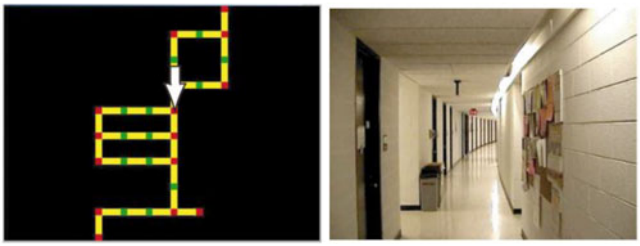

Fig. 3. Left: Example tactile map (with geometric info only). Right: Non-geometric information shown for current location on the pathway being explored during virtual exploration (from [70]).

no decrease in the metric structure for mental spatial relationships derived from tactile maps by individuals who are congenitally blind. This is in contrast to the results mentioned in Section 3.3.2 regarding mental spatial relationships derived through locomotion. Using a tactile map to form an allocentric representation also appears to benefit from providing instructions to use an allocentric frame of reference and a physical reference boundary at the edges of the map [69].

For individuals with low vision, the use of non-geometric pathway information (Fig. 3, right), such as doors, signs and lighting, can also improve performance to a degree equivalent to using a map [70].

3.3.4 *Neuroimaging Studies*

A few neuroimaging studies have examined the brain network that underlies haptic locomotor space perception ([71], [72]). These studies highlight the importance of the hippocampus and the parahippocampal gyrus in spatial navigation. For instance, in [71], congenitally blind subjects performed a virtual navigation task using a feedback device that translated a visual image of the current, local segment of a route map into electrotactile array stimulation applied to the tongue. The brain regions that are critical for visual space navigation (i.e., the intraparietal sulcus and parahippocampal gyrus) were activated by the recognition of previously learned routes (relative to “scrambled” routes) in individuals who were blind. When the same task was performed under full vision by individuals who were sighted, the activation pattern strongly resembled that obtained with the individuals who were blind with the feedback device. This result suggests that the same cortical network underlies spatial navigation tasks between the blind and sighted subjects.

Moreover, in [72], blind individuals (both early and late blind) and blindfolded sighted individuals performed several locomotor spatial tasks before undergoing MRI scans. These tasks were: retracing a learned maze route, pointing tasks from a given point back to the starting point and the previous pointing position, and determining which of five small scale models correspond to a freely explored spatial layout. Both groups of blind individuals performed better than the sighted individuals in the maze retracing task and the model matching task, and comparably to sighted individuals in the pointing tasks. From the MRI scans, the researchers also found that the volume of the hippocampus was greater for individuals who were blind compared to individuals who were sighted. The volume was also found to be correlated with performance. However, it should also be noted that the results for the maze tracking task and the model matching task are not what we would expect (see Section 3.3.2) for egocentric and allocentric tasks, respectively. It is possible that these differences from previous results and the larger hippocampus volume of individuals who were blind compared to sighted individuals may be due to significant differences in experience in haptic locomotor space perception.

3.4 Affective Touch (Tactile Pleasantness)

When we touch objects, we not only perceive and discriminate their physical properties such as roughness (discriminative touch), but also experience associated affective sensations such as pleasantness and unpleasantness (affective touch). The effect of affective touch experiences with an assistive technology product may have an impact on the product’s acceptance. For example, some surfaces, such as 3D printed plastics, are perceived as unpleasant by individuals who are BVI and potential users are more reluctant to explore objects built with this material. Designing surfaces that increase the experience of pleasantness during contact could also render users more comfortable when they interact with products. In addition, the dimension of pleasantness/unpleasantness could be used as a display parameter. This may be particularly beneficial for indicating safety warnings to a user due to the likely correlation between danger and the emotion of unpleasantness. The expected correlation could potentially decrease the cognitive processing time of the user’s response which could be essential for real-time situations. It is also potentially useful to control the degree of unpleasantness to indicate different danger/alert levels.

While affective touch has attracted considerable interest among scientists, most of the research to date has been limited to sighted individuals [73]. We will review it here. Further research with individuals who are BVI is important to ascertain any similarities or differences with sighted individuals.

3.4.1 *Object Properties that Produce Pleasantness and Unpleasantness*

One of the fundamental questions regarding affective touch is how it is related to discriminative touch. This is useful for the development of assistive technology by determining how levels of unpleasantness can be created and if unpleasantness can be treated as a dimension independent of discriminative dimensions.

The relationship between discriminative and affective touch has been investigated for material properties such as temperature [74] and roughness (e.g., [75]). These findings suggest that the similarity of behavior between discriminative and affective touch depends on the object property of interest. For temperature, although the perceived magnitude of the environmental/object temperature (discriminative touch) is independent of the participant’s body temperature, perceived pleasantness (affective touch) differs depending on the body temperature of the participant [74]. In contrast, perceived roughness and pleasantness/unpleasantness are highly related except in their relationship to scanning speed [75].

In general, discriminative touch focuses mainly on stable external objects and their various properties, whereas affective touch relates to how physical contact affects the internal state of the individual's body [76]. We expect an individual will use a product more often if it is made of object properties that the user is willing to explore haptically and if the product produces combinations of pleasant and unpleasant stimuli to help the user use it effectively.

3.4.2 The Effect of Body Site

Characteristics of affective touch can differ between the human hand and other body sites involving hairy skin. This is an important consideration in assistive technology design as sites other than the hands are often used. One significant design consideration is that, unlike the glabrous skin, the hairy skin uniquely contains unmyelinated afferents that respond to very low indentation forces and slow velocities such as by gentle stroking with a soft brush (CT afferents) [77], [78]. These CT fibers are hypothesized to represent the neurobiological substrate for the affective and rewarding properties of touch [73].

A second issue is related to skin structure and mechanics. The outermost layer of the epidermis is the stratum corneum, which consists of hard keratin that maintains homeostasis within the skin. The stratum corneum is substantially thicker on the hand than on the forearm, presumably serving to prevent the hand from being injured during frequent object contact during tactual perception and manipulation [79]. These differences may affect the perception of unpleasantness at different body sites. The neural and anatomical differences could be critical points to consider in designs for assistive technology dependent on the body site to be used.

4 EXAMPLES OF APPLICATION OF DESIGN INSIGHT FROM BEHAVIORAL RESEARCH

In this section, we show the utility of applying results from behavioral research to the design of assistive technology. We describe two examples where the results from behavioral theory were explicitly applied to assistive technology design and validated. Further potential design insights and their application will be considered in the Discussion section.

4.1 Material versus Geometric Information Processing

Lederman, Klatzky and their colleagues, have argued for the importance of local material properties (roughness, compliance, slipperiness, thermal conductivity) and coarse 3D global shape in identifying objects haptically. These properties can be acquired quickly and efficiently with the hands using the appropriate haptic exploratory procedures [80]. Abrupt 3D discontinuities also appear to play an important role in quickly identifying objects [81]. In contrast, obtaining exact shape information requires contour following which is a slow and memory intensive process. This suggests that, if a material property is diagnostic of an object, it may be advantageous to portray it in a haptic display for fast object recognition.

However, at the present, it is difficult to convey realistic materials accurately in haptic displays. An alternative, particularly for 2D graphical displays, is to use dimensions of material properties to encode information to help overcome the difficulties of interpreting the traditional raised line representations (Fig. 4, left). This possibility was examined by two research groups: one using hand-made paper displays [53] and the other using a haptic display [54].

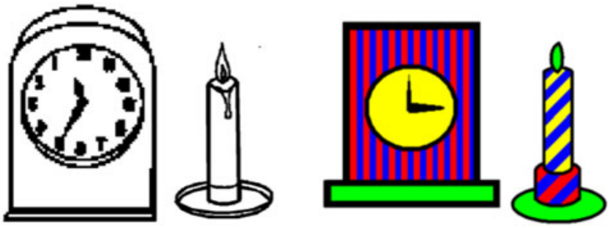

Fig. 4. Examples of raised line drawings (on left) versus textured drawing (on right) used in [82]. On the right, different colors indicate different temporal frequencies.

Both groups proposed using different "textures" to distinguish object parts from each other to alleviate confusion as to which lines belong to each part. The interpretation of a line can be difficult as some lines are created for perspective or have been occluded by another part. Methods were also proposed to indicate basic orientation of parts, another difficulty with interpreting raised line representations. In both cases, the ability to identify common objects in 2D diagrams significantly improved with the texturized diagrams as compared to raised line diagrams.

Another important aspect of material properties was determined by Lederman and Klatzky through the use of a search task performed across one or more fingers [83]. In the task, the participant was required to determine which finger had a target (e.g., a rough surface) amongst distracters (e.g., smooth surfaces) applied to the other fingers. They found that material properties and abrupt discontinuities (e.g., edge – no edge) could be processed in parallel across fingers at the same time. In contrast, spatially encoded dimensions such as relative orientation, which are needed to interpret detailed shape, have to be processed sequentially by focusing on one finger at a time.

The question arises as to whether parallel processing of textures can aid in a non-search task requiring the integration of information, such as identifying objects in a 2D diagram. The results from [54] indicate that increasing the number of fingers used to explore textured diagrams (Fig. 4, right) significantly increases the ability of individuals who are BVI to identify objects in 2D diagrams and decreases the response time. In contrast, increasing the number of fingers used to explore raised line diagrams (Fig. 4, left) did not improve the user's ability to identify objects or decrease the response time.

4.2 Distributing Cognitive Load

The bandwidths of both touch and audition are significantly smaller than that of the visual system they are intended to replace for assistive technology for individuals who are BVI. An important question is whether both touch and audition can be used together to provide more information than just one system alone.

The motivation for multi-modal presentations to convey information is that separate working memory processing resources exist for visual, verbal, spatial, tactile, kinesthetic, tonal and olfactory information [84]. This model would suggest that to avoid overloading one modality, information could be split with another modality to increase the throughput of information and improve performance. However, this does not occur completely in parallel as, although overall information capacity increases, individual modal capacity tends to decline during multimodal multitasking [84].

Recent work [85] examined the effect of dividing information amongst the haptic and audio modalities on an audio-tactile graphics display to improve performance (cf. to using either modality alone). Individuals who were BVI had to relate two types of diagram properties to each other. In one type of diagram (geographic diagram) participants had to identify the states of a country (property 1) where fruit is grown (property 2). In the second type of diagram (building map) participants answered questions relating to the layout of train tracks on the first floor of a station (property 1) to the layout of stores on the second floor (property 2). Performance improved significantly when the two types of diagram properties were represented in separate modalities rather than the same modality. Users also found the bimodal method easier to use.

However, the benefit of separating information between the audio and tactile modalities is likely to depend on whether the data is along the same dimension or different dimensions, and how the data needs to be cognitively processed. In addition, cross-modal interactions are known to occur in perception that may affect the strategy of using two different modalities to convey information at the same time (e.g., cross-modal attention, [86]). One caveat in considering the body of research on cross-modal interactions is that recent work suggests that audio-tactile cross-modal interactions may be reduced in individuals who are either early or late blind as compared to those who are sighted.

5 AREAS OF HAPTIC ASSISTIVE TECHNOLOGY

A variety of different types of tactile/haptic feedback have been used either alone or combined with audio feedback in several different areas of assistive technology for individuals who are BVI. In this article, we will focus primarily on systems using only tactile/haptic feedback. The application areas we will consider here, in turn, will be refreshable Braille, refreshable tactile graphics, orientation and mobility.

For both Braille and tactile graphics, pin type displays are most commonly considered. These displays can be based on a variety of technologies including piezoelectrics, solenoids and motors, smart materials (e.g., shape memory alloy), electrorheological fluids, and pneumatic and thermopneumatic actuators; see [88] for a review. Systems that sense the position of the moving hand and provide vibrational feedback to the fingers are also increasingly being considered. Force feedback devices have been considered for alternate "visualization" techniques, typically for presenting 3D shape, the physics of interaction in terms of force/motion relationships and/or data; one such application for education is given in Murphy and Darrah (in this issue).

Consideration of haptic devices for orientation and mobility have typically considered low cost vibrational feedback [89] through single or multiple eccentric rotating mass motors or linear resonant actuators mounted on various areas of the body.

Fig. 5. Top left, typical commercial Braille display (from [96]); Top right, microbubble actuator (from [92]; Bottom left, laterotactile display with pentagraph device (used in Levesque et al. [94]); Bottom right, Braille cell with graphics tablet (used in Headley et al. [97]).

5.1 Braille

It may be tempting, given the small portion of individuals who are BVI that can read Braille (only 10 percent [8]) and the prevalence of text to speech technology, to overlook the importance of providing effective displays for Braille reading. However, it is interesting to note that 90 percent of individuals who are blind and employed read Braille [90]. Two possible important issues are that Braille reading: (a) is an active process and this improves the retention of information (see Russomanno et al., this issue) and (b) allows individuals to hear (or overhear) colleagues and superiors to enable them to actively participate in their work environment.

5.1.1 Technology

Commercial refreshable Braille displays use piezoelectric technology that has been used for many years. The limitation of this technology is that it is expensive, which limits the size of the display that can be provided in an affordable device. Typical displays are 40 to 80 Braille cells long in a single line (Fig. 5, top left).

It has been argued that the "Holy Grail" of Braille is to provide full page text to allow navigation through the information using similar techniques to vision, such as feeling for the beginning of paragraphs. Although screen readers (which convert text on the computer screen to speech) also provide some comparable strategies if properly annotated (such as progressing through subsections of a text article), they rely on the writer to properly format the accessibility features and reading is unavoidably serial in nature.

Braille printers that can provide full page Braille do exist, but they are time consuming and expensive to use. The resulting product is also very bulky and wears with time. Some of these printers are also able to print graphical content, but still have the same limitations as those that can only print Braille.

More recently, researchers have considered alternate technology that could plausibly be efficiently produced for a full page display such as using electroactive polymers (e.g., [91]), or pneumatic and thermopneumatic actuators (e.g., Fig. 5, top right, [92]). Another important aspect for production is the electronics that are needed. Existing line displays set the Braille pins sequentially and they then remain static while the user reads them. This makes the electronics simple and efficient, but too slow for a full page of Braille. Several groups have developed more effective electronics to address this issue, such as in [93].

In contrast to most displays, which consider movement in the normal direction, Levesque et al. [94] created a novel method of producing the sensation of brushing over a Braille dot by lateral skin deformation using deflecting piezoelectric benders. This display was used in combination with a low-friction slider to produce Braille cell rendering (Fig. 5, bottom left). Unfortunately character recognition was poor, with an average of 57 percent, but it is possible that better understanding of the mechanics of Braille reading could lead to improved algorithms.

5.1.2 *"Virtual" Braille Displays*

An alternative to developing technology to decrease the cost of Braille cells is to design displays that retain the effectiveness of larger displays while using fewer cells. In order to achieve this result, behavioral studies of Braille reading are important to understand (Section 3.1); although it may be possible that alternate methods of reading may prove effective as well. One idea developed by a team at the United States National Institute of Standards and Technology was to produce a low cost line display using a drum to continuously slid Braille cells across the finger in a circular queue. The number of cells needed for their drum was far less than for a 40-80 cell line display [95]. This method allowed passive sliding across the finger, which is important for Braille interpretation, but not active exploration, which is also important (Section 3.1).

Other designs have focused on providing the ability to actively explore a virtual page with a single (or small number of) Braille cells, but without the Braille display actually physically sliding across the finger (Fig. 5, bottom right). Perhaps the earliest version of this type of design was the Optacon [98], although it differs from many of the more current devices in that it used one hand to provide the kinesthetic input and the other hand for the display. In particular, an optical device was used in the first hand to explore a physical page to read print text, while a multi-pin vibrotactile display in the other hand provided the corresponding Braille feedback. Some users, after training, were able to use the Optacon very effectively; however, many users had difficulty. This was most likely due to the pins being vibrated at 250 Hz—a temporal frequency that has poorer spatial resolution compared to lower frequencies [15]. The separation of the kinesthetic from the tactile information between the two hands also potentially increased the difficulty.

More recent devices ([97], [94]) avoid the problems of the Optacon by not using high frequency vibrations and by providing feedback to the exploring hand itself. However, there is still a potential problem with these devices since there is no relative motion between the pins and the finger pad as occurs when reading Braille on paper. The typical method of rendering the information, which is based on the current pixel value from the "picture" to be rendered, is problematic for presenting Braille. This is due to the contact of the pins with the finger pad being very brief and, therefore, very difficult to interpret. In [94], extending the width of the dots and providing other enhancements still produced poor performance. However, in [97], a spatial window on the virtual "picture", used to maintain a static character on the Braille display, produced very good performance in reading letters (97 percent correct). It is not yet known how performance using the static characters on the Braille display changes reading rate compared to traditional methods of using a finger to slide across a Braille cell.

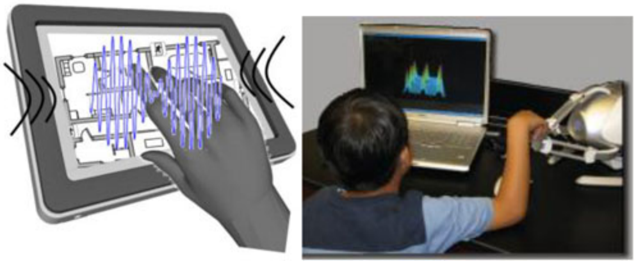

Fig. 6. Left, use of tablet computer's built in vibration; Right, use of force feedback device (using a Novint Falcon).

5.2 Tactile Graphics/Visualization

Traditionally tactile graphics have been made by hand using material scraps, using thermoform and swell paper techniques, and on Braille printers that provide higher resolution. One technical modification to these diagrams is to provide additional speech information through the use of, for example, a graphics tablet [99] or QR codes [100]. Others have considered the use of physical, tactile overlays to aid with extracting information from a touch screen [101]. Two important advantages of displays that are entirely refreshable are that: (1) they do not require the physical creation of a graphic, which can be slow and expensive, and (2) it is easy to provide dynamic diagram manipulation software to facilitate haptic diagram interpretation, which is typically a slow and difficult process. Two issues that we will consider in this section are software algorithms for zooming and simplification; both of which have been considered important for diagram interpretation (see Section 3.2).

5.2.1 *Tactile Graphics Displays*

Although it is possible to produce a refreshable tactile graphics display by combining a large number of higher density "Braille cells", the cost is prohibitive to most individuals who are BVI. Most displays for tactile graphics use a similar concept as the small but mobile tactile displays used for Braille. In this issue, Brayda and his colleagues assess the importance of visual experience, gender and emotion in the assessment of an assistive tactile mouse. Systems with a single contact for each finger have been considered as well. An interesting possibility for a single finger contactor is the use of the built in vibration of tablet computers based on the location of a finger on the screen (Fig. 6, left;

e.g., [102]). Multi-fingered feedback can be used with external vibrators [54], whether to multiple fingers on the same or both hands. Alternate technology is also available for single finger feedback by modulating the frictional force [103].

Two important aspects in the design of these mobile display systems are: accurate position measurement within the virtual display and a fast response time of the tactile pins/vibrator(s) to render the spatial information of the picture accurately. It should be noted that the use of position sensing technology of regular mice (often considered or used) is not sufficiently accurate for tactile diagrams for individuals who are BVI [104], although it may appear adequate with vision.

5.2.2 Tactile Rendering

There has been a lot of work considering tactile rendering in general through pin type displays and vibrators in the haptics community. Here, we will specifically focus on the work of those who have considered tactile graphics for individuals who are BVI. Rendering has typically considered raising and then lowering pins for edges (for pin displays), as well as different types of vibrations, spatially created textures, and/or temporal or spatial modulation of these signals for points, lines or areas (e.g., [54], [105]). Variations in the height of pin(s) [106] or other mechanisms [107] have also been considered to convey information.

One of the difficulties with small moving displays is that the spatial information is not fine enough to quickly track lines. Rather than smoothly following a line as with a physically raised line diagram, individuals typically need to sweep back and forth across the line to maintain contact while tracking. One alternative is to provide area rather than line information when possible (such as for an object's part) which does not "disappear" as easily as a line. Another possibility proposed by Pietrzak and his colleagues is to use pin array tactons to indicate the direction the user should move to follow a line [108]. Their group also proposed that pin array tactons could be used to represent whole diagram elements, such as components of an electric circuit (battery, resistor, capacitor, junction, wire, etc.).

5.2.3 Zooming

As the spatial acuity for touch is much poorer than for vision, magnification of parts of a diagram is often needed if details are to be interpreted effectively. Even if details are perceptible in the original diagram, performance is significantly better with larger pictures [55]. For physical diagrams, TVIs will decide which parts of the diagram need magnification ahead of time and provide a separate diagram for them. Providing zooming for refreshable displays makes this more flexible and under the control of the user.

Several research groups have applied visual techniques, such as smooth zooming (albeit with force feedback detents) [109], and linear or logarithmic step zooming [110], [111]. As the appropriateness of visual zoom levels is usually judged by inspection by the user, which can be very tedious with touch (due to the slowness in exploring diagrams), an alternate technique has been proposed based on object (and subobject) hierarchies of a diagram that were traversed with each zooming level [112]. Comparison of the use of this new method to linear and logarithmic step zooming techniques for answering questions about diagrams by individuals who are BVI found that both the correctness of the answers and the method's usability were significantly better for the new technique.

5.2.4 Dynamic Simplification

In physically created tactile diagrams, simplification by removing content is a critical part of the process in making a diagram manageable to read by touch. In addition, complex shapes may be replaced by simple polygons if the details are not needed. For physical diagrams, TVIs typically remove all content and details not relevant to a child's lesson plan; however, this requires knowing what will be relevant ahead of time and greatly limits incidental learning. For working adults, what is relevant is not usually known a priori.

Refreshable displays provide an opportunity to allow users to select themselves what content they would like simplified. Two cases where improved performance was found were: maps with multiple sets of features (e.g., states of a country, topology, weather, industries, etc.) and maps of countries which included state and country boundaries [113]. In the first case, participants who were BVI were asked questions relating features within two feature sets (e.g., "Identify the state with the largest number of coal fields"). They were then allowed to select what feature sets they wanted visible on the refreshable display when determining their answer. In the second case, participants were asked to identify the shape of the country and the number of states in it. They could select between using the original diagram or a diagram made from polygon simplification. In both cases, the number of correct answers increased significantly.

In contrast, no difference in the number of correct answers was found in another task where participants who were BVI were allowed to choose between using a complex diagram or toggling between the complex diagram and a simplified diagram [114]. In this study, participants were asked to find a seat location in a concert hall and were given either the complex diagram alone, consisting of section boundaries and seat locations, or both the complex diagram and a simplified diagram containing only section boundaries. The difference in results compared to the previous study may be due to the questions asked, as not all questions are expected to benefit from simplification.

5.2.5 Force Feedback Display Methods

Many research groups developing assistive technology to aid with "visualization" by individuals who are BVI have considered using force feedback devices (Fig. 6, right), sometimes including audio feedback as well (for a review non-specific to individuals who are BVI, see [115]). Some research groups have used haptic rendering techniques similar to those used for sighted individuals for virtual reality environments (e.g., [116]). Unfortunately, without vision, the haptic feedback becomes very difficult to use to determine 3D shape.

Other groups have primarily focused on providing methods to explore graphs using virtual fixtures to reduce the difficulty in trying to find a line and follow it. For example, several groups have created attractive forces to lead a user's hand to a line and then allow the hand free movement along the data line itself (e.g., [117]). Others have mixed this technique, or a similar concept of modeling V-shape grooves for lines, with audio, speech and vibrational feedback to assist users (e.g., [118]). This method, in conjunction with other concepts, seems to improve performance [118] but further experiments are needed to tease out which factors contribute most.

5.3 Orientation

For the purposes of this paper, we define orientation as: "The knowledge of one's distance and direction relative to things observed or remembered in one's surroundings and the ability to keep track of these spatial relationships as they change during locomotion" [119]. A haptic orientation aid is a device that provides kinesthetic and/or tactile feedback that augments or replaces orientation-related information typically provided through vision. As described previously in Section 3.3.1, orientation can be in terms of an egocentric framework (with respect to oneself) or in an allocentric framework (external to one's self). Giudice and Legge [120] provide a review of some technology developed for orientation, as well as mobility, although not necessarily using haptic/tactile feedback exclusively.

5.3.1 Waypoint Navigation

Outdoor waypoint navigation capabilities, enabled by ubiquitous access to Global Positioning System (GPS) signals, have led to a number of developments in mobility support technologies for individuals who are BVI. GPS does not work indoors, but many research groups and companies (large and small) are working on indoor localization technology systems for mainstream commercial applications, as well as aids for individuals who are BVI. Auditory feedback, in the form of speech, is the most common mechanism for providing directions from point to point. However, it does have the disadvantage of potentially obscuring other important sounds. Tactile feedback accesses an otherwise underutilized sensory channel and thus its use can potentially reduce cognitive load [121].

A straightforward method of providing tactile information for waypoint navigation is the marriage of a GPS receiver with a Braille display/notetaker [122]. These systems allow route planning using stored map data and provide on-the-go directions via Braille. Disadvantages of using a Braille display as a navigation aid include the fact it occupies at least one of the user's hands during operation and that not all individuals who are BVI can read Braille. These issues, in part, have generated interest in hands-free options (which have considered using the torso, back, tongue, foot and wrist), although some methods being considered continue to use displays for the fingers and hands.

One simple approach to provide direction via non-Braille touch is to generate a vibration somewhere on the body if the user is within a certain tolerance of the correct heading [123]. A slightly more complicated approach is to alternately apply tactile feedback at two body locations to indicate to turn right or left, for example, using actuators on the shoulders [124] or wrists [125]. The desire for more precise information has led to the development of torso-worn tactile belts. For example, Van Erp successfully demonstrated the use of vibration location to convey direction with an eight tactor linear array [126].

For torso-worn belts, adding additional feedback positions on the body to spatially indicate the direction to move in can enhance the resolution of directional cues. Research indicates that a 10 degree angular discrimination is achievable [127]. A recent study demonstrated the use of a tactile belt to provide rotational (orientation) cues in addition to directional information [128]. In this issue, Flores and his colleagues compare the use of a vibrotactile belt to audio guidance in a wayfinding task. The authors found the belt provided closer path following, but at the cost of reduced average speed in task completion.

5.3.2 Survey Knowledge

Several researchers have demonstrated the effectiveness of synthetic speech in conveying the spatial layout of rooms, hallways, and other building features (e.g., [129]). The same concept has been applied to GPS-based systems that provide "look around" text-to-speech rendering of information on outdoor points of interest such as street intersections, restaurants, shopping, and entertainment [130]. Such audio-only systems are practical but only partially meet the definition of orientation – they lack the elements of relative distance and direction between objects that are most often conveyed via a map.

Map exploration offers a direct means of acquiring an allocentric cognitive representation of spatial layout and content, which is needed for representing survey knowledge. This type of knowledge (as opposed to route knowledge) appears to be critical for formulating short cuts, detours, novel routes and recovery from disorientation [131]. For individuals who are congenitally blind, maps have been shown to be necessary for acquisition of survey knowledge, which is not naturally acquired by these individuals by walking through a space (see Section 3.3.1).

Physical maps have also been combined with electronics to create a Talking Tactile Tablet [99] in which the maps become touch-sensitive and render audio content associated with the region under exploration.

A few groups have considered the creation of refreshable vibrotactile maps of varying complexity on smartphones and/or tablets. Poppinga et al. [132] considered simply turning a vibration on when passing over roads, combined with speech output naming the road. Klatzky et al. [133] considered slightly more complicated vibratory effects that could be generated with the UHL effects by Immersion Corporation, namely two different vibrating lines and pulsing information points, combined with auditory effects using a pitch/vertical association. Assessment of usage with sighted subjects for simple line graphs found no difference in performance when using the audio alone, vibrator alone or both together, although users seemed to have a preference for using the auditory information, whether alone or combined. An ongoing project involving Adams and Pawluk considers a wider variety of vibrotactile elements, combined with sonification and speech, which is being assessed for an indoor navigation task by individuals who are BVI.

5.4 Mobility

We define mobility as "The act or ability to move from one's present position to one's desired position in another part of the environment safely, gracefully, and comfortably" [119]. A haptic mobility aid thus can be defined as a device that provides kinesthetic and/or tactile feedback to aid in ambulation and avoiding obstacles in a proximal context.

5.4.1 The White Cane

The most ubiquitous haptic mobility aid has been the long cane, which most people think of as permitting physical contact with obstacles at an approximate 3 foot range as well as a visual warning to others to give way [13]. However, the white cane can provide much more information. Its effectiveness, ease-of-use, ease-of-replacement/repair and low cost make it a benchmark for new assistive technologies. On the most basic level, a cane will be used to systematically sweep the environment to detect objects in front of the user and can be used as a method of trailing parallel to walls, drop offs, texture changes and seams using physical contact [134].

A cane can also be used to facilitate echolocation of objects beyond the reach of the cane (including to the side of a person or overhead), as well as to enable the user to walk parallel to walls without contacting them. Vibrations to the hand provide essential information about ground surfaces that are ahead of the person, delineating such things as sidewalk, grass or driveway. Deaf-blind individuals are encouraged to use canes that are superior in resonance and tactile feedback for mobility in place of the use of sound [135].

5.4.2 Obstacle Avoidance Systems

Assistive technology for mobility typically uses sonar, laser or video camera(s) to sense the environment while providing audio or tactile feedback to the user in combination with kinesthetic feedback in place of vision. A recent review of several devices is given in [136]. Historically, auditory cues have been the preeminent means of feedback in both orientation and mobility aids, due to the substantial information transfer capacity of the sense of hearing. Unfortunately, the use of sound necessarily masks subtle auditory cues employed by individuals who are blind [13]. Haptics thus provides an alternate channel through which human sensory information can be conveyed.

Haptic aids for obstacle avoidance have existed for at least 50 years. Two of the earliest examples involved using an ultrasonic transducer to detect an object in front of a user [137], [138]. These devices were intended to be used in conjunction with a white cane and/or guide dog. The Travel Path Sounder [137], worn around the neck, used audio and tactile cues to provide warnings and a rough indication of distance through three discrete feedback levels. The Mowat sensor, similar to the currently available Miniguide (see Fig. 7), is a hand-held device providing vibratory feedback with a frequency inversely proportional to the distance to an object [138].

Several groups have proposed using a technology-enhanced cane to provide information about obstacles. Tactile feedback from these devices consists of a set of from 1 to 16 vibrators on the handle to convey information either to general points on the hand or to very specific pads of the finger (e.g., [139]). The feedback provided by these devices varies from a simple alert to more complex information about distance and direction of an obstacle. In this issue, Kim and her colleagues investigate a range of spatial and temporal feedback patterns for conveying obstacle distance information using a cane-integrated tactile display. One commercially available enhanced cane is the UltraCane [140]. It uses two ultrasonic transducers: one to detect obstacles in the forward direction, the other to detect overhanging objects that would be missed by a traditional cane. Two vibrotactile buttons in the cane's handle provide feedback on distance to an upcoming obstacle and whether it is low or high with respect to the user.

Fig. 7. Top left: Vibrotactile belt that has been used for either navigation or obstacle avoidance, from [128]. Bottom left: using the Miniguide. Right: Guidecane, from [142].

Other groups have proposed wearable obstacle avoidance devices that, similar to those for navigation, place vibration displays on a variety of parts of the body (e.g., head, hand, wrist, abdomen, back, waist, etc.) Some of these devices are reminiscent of the tactile visual substitution system of Bach-Y-Rita (see Section 2.2.1). Some require that the user sweep the environment with a hand held sensor to detect the obstacles. Others embed their devices into shirts or vests.

Unlike the other haptic mobility aids mentioned thus far, which rely on tactile cues, the GuideCane (Fig. 7, right) generates kinesthetic (force) feedback [141]. The design attaches a cane to a two-wheeled robot equipped with an array of 10 ultrasonic transducers. When the robot detects an obstacle, it exercises internal decision logic to steer itself away from the object (by torqueing the steering assembly). The user feels the change in direction through the movement of the attached cane. Once past the obstacle, the GuideCane reacquires the original course. A notable disadvantage to this sophisticated approach is that the blind user becomes a (passive) follower of the robotic system – potentially impeding spatial learning [120].

Another variation on a haptics-augmented white cane by Gallo and his colleagues provides both tactile and kinesthetic feedback [143]. The design employs braking of a spinning inertia mechanism to impart torques that imitate the impact of the cane with a real object. Three vertically aligned vibrating motors in the handle convey distance using the sensory illusion of apparent motion.

6 DISCUSSION

The significant difference in the way information is processed in the visual and tactile systems suggests that for assistive technology one cannot simply map a visual scene on to the skin to convey the information. One must use a smaller subset of information and look toward different methods to facilitate information transmission through the tactile/haptic systems. User testing is also a difficult task as there are several characteristics of an individual user, such as medical condition, experience, opinions, preferences and motivation, which can affect performance. Some of these variables, such as motivation, have hardly been studied.

In this discussion we focus on the reciprocal benefit between behavioral studies and the development of assistive technology, issues regarding neuroplasticity and learning, and more specific issues in regard to our four major areas of assistive technology, Braille reading, tactile graphics, orientation and mobility.

6.1 Using Behavioral Information

Results from behavioral research with individuals who are BVI in areas needing accommodation, such as reading, accessing graphics, orientation and mobility provide a rigorously tested conceptual foundation to develop assistive technology. Although most, if not all, developers of assistive technology targeting the BVI population do use information provided by behavioral research for assistive technology design, this is often in terms of applying specific facts such as the spatial resolution of touch. However, as our examples in Section 4 attempted to show, translating and validating concepts from behavioral research with BVI subjects and general behavioral research provides us with a foundation to construct design methodologies. Focusing on this foundation would allow future designers to build on current work rather than starting "from scratch".

Also, there are some types of stimuli (e.g., electrotactile) and skin target site (e.g., trunk and arm) for which designers have significant interest in using but have not been well studied behaviorally. For example, despite the fact that the structure of the skin/subcutaneous tissue and the mechanoreceptors present varies significantly based on target site, little work has examined such basic information as the temporal frequency characteristics at these sites except for the fingers. For cylindrical surfaces, such as the trunk or arm, we are also unaware of any work examining what happens when spatial tactile patterns are wrapped around the whole "cylinder" rather than only on the "front" or "back". This would potentially provide more space for presenting information. Finally, despite the practical advantages to creating electrotactile arrays, there has been relatively little work in understanding the phenomena that these devices create.

6.2 Validating Assistive Technology

Currently most assessments of assistive technology are in terms of user performance and user acceptance for the particular prototype developed. Unfortunately this does little to advance the field as most researchers use different testing tasks, which makes it very difficult to compare different prototypes by different researchers and draw conclusions. A regime of tests to be used by developers of different technology applications could alleviate this problem. However, often these prototypes have multiple differences which make it difficult to extract generalized concepts. More studies are needed that cleanly vary different conceptual variables to provide a foundation for future design efforts.

In addition, both psychophysical and neuroimaging techniques can be used to investigate the strategies utilized with assistive technology to potentially evaluate their ease of translation. For example, Kupers et al. [71] found that the brain activation patterns when early blind individuals perform a virtual navigation task with a tactile display strongly resembled that of sighted individuals with full vision. This suggests that it is possible that a similar strategy is used in both cases.

6.3 What Does Neuroplasticity Mean for Assistive Technology?

One of the most interesting findings from the neuroimaging literature is that the primary visual cortex only seems to be recruited for Braille reading and other tactile discrimination tasks in individuals who have lost their sight before age sixteen [36]. This was used as a division between individuals who are "early" and "late" blind. However, the division between "early" and "late" blind used in Section 2.1 was based on visual experience rather than plasticity and occurred at a much earlier age. This suggests that the single division early/late blind should not be used in studies as multiple changes occur at multiple time points as individuals develop. Rather, participants in experiments should be described in terms of age of onset of blindness and the results related to the several developmental changes that occur over the early years.

In addition, because the above result appears to show that neuroplasticity is more pronounced in BVI individuals with an onset of blindness before age sixteen, it is recommended that difficult tasks, including those that use assistive technology, be introduced at a young age when possible. However, this cut-off age may not be as strict as implied in [36] as sighted, presumably adult, Mah-Jong experts also showed activation of the primary visual cortex for the tactile discrimination of Mah Jong tiles *and* Braille [7]. Further study is needed to determine what type of tactile training at later ages can lead to usage of the primary visual cortex and how this can benefit performance in sensory substitution tasks by individuals who are BVI.

However, it is also not clear how important a role the primary visual cortex plays in task performance. Although Sadato et al. found that task performance positively correlated to the activity of the primary sensory cortex in [36], two subjects who lost their sight after the age of sixteen performed equally well to those who lost their sight before the age of 16. These two subjects did not exhibit an increase in activity in the primary visual cortex. Their results are positive indicators that achievement of high performance is not necessarily restricted when neuroplasticity is more limited, although there are possibly significant differences in the cognitive processes involved.

Conversely, equivalent performance between the "early" and "late" blind does not mean that the same cognitive processes are involved. This means that changes to a task method where equivalent performance is found, such as introducing assistive technology, could actually affect performance very differently between the two groups. Therefore, it is important to assess performance with any proposed assistive technology with users of the two groups to validate its usage with potentially different cortical processing methods.

Tactile stimulation of the relevant skin area and, possibly, continuous performance of a tactile/haptic task over an individual's life time may also be necessary to develop *and* maintain the new cortical connections. For example, the size of the primary somatosensory cortex dedicated to the Braille reading fingers is known to be larger in the early blind than the sighted [47]. This seems consistent with neurophysiological work in owl monkeys showing an expanded cortical representation for skin areas which were repeatedly stimulated [144]. However, subsequent repeated stimulation of other skin areas would again dynamically change the overall primary somatosensory organization, including possible losses in the aforementioned expanded areas if the previous stimulation is no longer repeated.

Higher areas of the visual cortex appear to be multisensory areas with visual, tactile, auditory and possibly other sensory inputs. In congenitally blind cats, the areas for somatosensory and auditory input seem to expand into the visual areas of multisensory cortical areas in the absence of visual inputs [145]. Auditory processing and linguistic processing, in addition to tactile processing, are known to take over the primary visual cortex [145]. This may add further competitors for space in these cortical areas.

6.4 Should Assistive Technology Be Designed to Encourage and Accommodate Learning?

The observed changes to brain organization suggest that learning and practice are an important part of adapting to and effectively using sensory substitution. However, in addition, some behavioral differences found between individuals who are early blind and those who are sighted or late blind are suggested to be due to lack of exposure (i.e., lack of opportunity to learn) rather than inherent limitations of the early blind population. For example, Heller and his colleagues [56] argue that it is exposure to the rules of perspective in pictures that is important to its understanding, rather than exposure to vision. What is the responsibility of developers of assistive technology to teach these rules rather than provide an alternate method of accessing this information?

One example is when exploring locomotor space, both sighted and late blind individuals can use an allocentric framework whereas early blind individuals cannot. Individuals who are early blind can, though, construct allocentric frames of reference when using tactile maps. This suggests that assistive technology providing tactile maps is essential for these individuals when performing allocentric related tasks in locomotor space. However, the ability of late blind individuals to use an allocentric framework suggests that it is not the presence of vision that is needed but exposure to vision or, perhaps only, exposure to the rules of allocentric frameworks. This suggests that assistive technology may be successfully developed that uses tactile maps and other components to train individuals who are early blind how to construct allocentric frames of reference solely from the environment. This would provide these individuals with greater autonomy when tactile maps are not available.

However, what does this mean for issues such as recovering the development costs of the assistive technology? Potential users may be less motivated to purchase a device if it is only needed for a short period of time, assuming it is of little value. Tactile maps will likely still be desirable to use even after individuals are able to form an allocentric representation without a map, as is true with visual maps with sighted users, but what about other technology? Anecdotal evidence from the Visual Impairment Services Outpatient Rehabilitation at the Hunter Holmes McGuire VA Medical Center suggests that this may be, for example, problematic for obstacle avoidance technology. The few users who have used electronic obstacle avoidance technology in their program always transitioned later to the use of a white cane. The electronic technology may have been critical in the learning process but it is unclear whether the users and the rehabilitation staff appreciated its value. This has resulted in the staff being less likely to recommend the technology to potential users.

Whether encouraging and accommodating this type of learning is “built in” to assistive technology or not, it may still occur with potential consequences for the long term viability of the product. Documenting the advantage of a particular assistive technology to the learning process may circumvent problems with user perception about the product's value.

6.5 Print Information: Should Full Page Braille Be the Goal?

Several groups, such as the National Federation of the Blind, consider the ability to read and write Braille an important precursor of success in education and the workplace. Braille is thought to give the same access as the “printed word” by allowing the user to experience the information spatially and actively control his/her focus. Braille is also considered essential for note-taking and helpful for studying math, spelling and foreign languages [146]. However, current refreshable displays are expensive and fewer than 10 percent of individuals who are BVI in the United States know Braille [8]. In addition, the number of Braille characters that can fit on a page is significantly more limited than “print”, which may reduce the advantage of experiencing the information spatially.

Previously in Section 5.1, we discussed small pin-type displays that were created to move over a page to provide access to a “full page of Braille”. However, whether modifying the presentation method can achieve reading and error rates comparable to reading a full page of physical Braille is not yet known. It is also worthwhile to consider another possibility, namely, to apply what is known to be effective about Braille reading to electronic speech generation.

Currently for electronic speech generation, speech is generated in a serial stream with no spatial component and very few active components. The latter may be limited to adjusting the speed of the speech and scrolling through a list of section titles to move to different parts of the text. It should, therefore, not be surprising that listening to text is not as effective as actively reading visually in terms of focus and comprehension [147]. However, speech generation remains a very affordable method of accessing print information. Can current speech generation methods be modified to incorporate the successful aspects of Braille—namely, providing both active and spatial access?

One possibility is that instead of using physical Braille characters, we could consider a virtual block of space on a page to correspond to a spoken phoneme or word. A touch screen could then be used to physically represent a refreshable version of the page, with the user's fingers being tracked to access the virtual verbal content. The speed of the reading finger could control the rate at which the speech is spoken. Knowledge of hand movements when reading Braille (see Section 3.1) would be essential to ensure that speech would only be produced from the reading finger, particularly when reading is transferred from one finger to the other.

One potential difficulty with this method is that no tactile feedback is provided to maintain a user's finger on a line or to find the next line. This could be overcome by using a tactile "overlay" for the touch screen, analogous to those proposed in [101], that would provide a physical guide for the user to follow lines, and detect their beginnings and ends. This physical tactile overlay could be combined with vibratory feedback on the screen when the reading finger passes over, for example, found search terms, or, in "editor mode", spelling or grammar mistakes. Having an editor mode would also allow text to be written, as well as read, in an accessible spatial layout. Furthermore, gestures could be used to query about the spelling of words and other aspects of the symbols used.

Due to the increasing number of elderly in our society, resulting in an increasing number of individuals experiencing visual problems with less motivation to learn Braille, we believe the exploration of alternate presentation methods of print information will only increase in importance with time.

6.6 Tactile Graphics and Spatial Acuity

The difference between the spatial acuity of touch and vision must be considered when conveying information normally presented visually through touch. Even if fine visual details are applied to the skin, it does not mean that the tactile system will be able to sense this information. However, Millar [148] has suggested that the spatial resolution measured by passive touch, typically used to define spatial acuity, is not necessarily the most appropriate measure for the legibility of Braille patterns. She suggests that movement cues are also extremely important. With movement, the spatial pattern can be recognized by the changing location of each of the points on the pattern as a function of time. This may be particularly advantageous when the tactile spatial resolution is limited [149].

The question then arises: what is the appropriate spacing of the tactile elements in a pin-array type of tactile display? If we consider the minimum distance a point needs to change location to be detected, as would potentially be done with a temporal code, we find that the distance detected can be less than 0.2 mm on the fingertip [150]. However, this is not a practical spacing for an electromechanical display. One possibility is to provide a combined electrotactile and tactile display (e.g., [24]) with the electrotactile display stimulating the densely arrayed receptors near the surface of the skin and the electromechanical display stimulating deeper receptors. Alternately, studying what element spacing is sufficient for a user to perform the required tasks may have less demanding requirements than trying to match the maximum performance of the tactile system.

The pin spacing needed is also dependent on the type of display used. Small pin-array tactile displays which are then moved about a virtual page can render spatial details of the information (e.g., a graphic) by creating temporal variations on the tactile elements, somewhat analogous to the benefit of moving the exploring hand. Therefore, the movement accuracy and temporal response of the display also contribute to how accurately spatial details can be rendered. In contrast, larger, stationary displays can only provide the information spatially and, are thus limited by their pin spacing. Even, if the hand moves across the display, it does not obtain more spatial details of the information (e.g., a graphic).

However, the ability to track lines or edges easily and quickly on a graphic is also important as the interpretation of detailed spatial information is primarily a serial process involving contour following. This issue also seems to be dependent on display type. With large, stationary displays, users do not experience difficulty in tracking lines/edges. When the finger is slid along this type of display, the pins stay in contact with the finger. The temporal response of the movement of the physical pins allows the user to easily resolve the line/edge orientation for tracking. In contrast, small moving displays with the same spacing usually result in slow and difficult tracking. With the latter type of display, we have observed that most, if not all users, need to scan back and forth across a line/edge in order to track it. This is because there is no physical motion of the pins on the finger and, therefore, only a brief contact with any one point on a diagram is made. This prevents obtaining a temporal response of the movement *of the line/edge* to determine orientation. The lack of physical motion of the pins is also why it is difficult to read Braille with these devices unless modifications are made as to how the Braille is presented (Section 5.1.2).

Further study of static and moving displays are needed to better understand what tactile information they convey, how users process this information, and at what resolution. Both types of displays are fundamentally different than using physical paper or plastic methods which provide a continuous form rather than a discrete one. How to more effectively convey information on these displays, particularly in regard to their weaknesses, is an important consideration for the development of effective access to refreshable tactile graphics. It is possible that a mixed electrotactile-electromechanical display, as described previously, may be beneficial in both cases.

6.7 Other Considerations in Creating Effective Refreshable Tactile Graphics

Spatially exploring a diagram, even with multiple fingers and both hands, is often a slow process compared to beinge able to perceiving a visual picture "all at once". However, tactile perception also has a very rich temporal component that has been considered for providing alerts, directions, and locations and distances of obstacles. This component has been applied to a much lesser degree in aiding the interpretation of tactile graphics. Section 4.1 gives an example of successfully using the temporal component of a tactile stimulus to create "textures" to improve the interpretation of tactile graphics. Using different vibration frequencies would also likely be an effective way to distinguish between multiple lines in a graph in place of dotted and dashed lines, which are difficult to interpret with the existing pin spacing of graphics displays.

Another avenue to consider is motivated by a proposed method to display tactile graphs by "collapsing" the y-dimension of the graph in Cartesian space and representing it by an auditory frequency [133]. As the user physically scans along the x-axis, the auditory frequency gives the y-coordinate while a tactile vibration indicates the symbol or line type. However, another possibility, instead of tactile vibration, is to separate different symbols or line types by auditory timbres that include harmonics. This would allow the natural segregation of the different timbre sounds into streams through auditory grouping [151]. This may make the information easier to interpret. Alternately, using tactile timbre with tactile frequency may open up possibilities of stream segregation in the tactile domain. We are not aware of any research that shows that stream segregation is possible in the tactile domain. If feasible, it could provide a novel method of temporally conveying multiple streams of information. It could also reveal that touch shows similarities to both vision and hearing in perceptual organization.

6.8 Consideration of Displays for Orientation and Mobility

One of the most significant concerns when designing and testing displays to aid with orientation and mobility is that they will be used at the same time when a user moves from place to place. This means that it is important to consider the cognitive load of the other tasks when assessing performance with the task under consideration. This is possibly best controlled by using a standard secondary task, such as performing mathematical calculations, to assess cognitive load. It should also be noted that the time scales of usage may be very different for the different tasks and may need to potentially be mimicked. For example, feedback for avoiding obstacles needs to be supplied quickly and continuously. Navigation instructions may be supplied less frequently, as long as notifications are given sufficiently in advance before intersections. Survey map information may be used even more infrequently and users are likely to stop and remain stationary while they explore a map.

An important consideration for design may be to distribute the cognitive load of the tasks between multiple senses to maximize the amount of information that can be held in working memory (see Section 4.2). The most effective and simplest method may be that one task (e.g., giving navigation instructions) provides feedback through audition, while the other task (e.g., obstacle avoidance) provides feedback through touch. This design is also less likely to have unexpected interactions between the feedback for the two tasks. This may be particularly true for individuals who are BVI as recent work suggests that audio-tactile cross-modal interactions may be reduced in individuals who are blind (e.g., [87]).

7 CONCLUSIONS

The history of the application of touch and haptics to assistive technologies for individuals who are BVI is long and varied. In this review, we have shown that there is a wealth of behavioral research that is highly applicable to assistive technology design. In a few cases, conclusions from behavioral experiments have been directly applied to design with positive results. Further controlled experiments assessing the application of other behavioral research concepts to assistive technology design are needed to provide a methodological foundation for future designers. Neuroplasticity in the brain and training users in cognitive concepts, as opposed to only training a user how to use a device, are also important aspects that need to be considered when designing *and* assessing assistive technology. Both can potentially result in considerable differences in user behavior over time, and the cognitive processes involved may be dependent on when a user has become blind.

The development of assistive technologies for individuals who are BVI also raises interesting behavioral questions. For example, given practical restrictions on device design, such as performance limitations of the technology and cost, which aspects of these restrictions are truly important to overcome to achieve high performance and which are not? In general, this raises the question of what it means to provide functional equivalence as opposed to sensory equivalence. In addition, when functional equivalence can be provided by a variety of methods, both psychophysical and neuroimaging techniques may be effective in determining the potential ease of learning a given method. The user's environment, including the use of other assistive technology, will also have an impact on the ease of use.

ACKNOWLEDGMENTS

This work was supported in part by the US National Science Foundation Grant #1218310 to Dianne T.V. Pawluk and the Japan Society for the Promotion of Science Grant-in-Aid for Young Scientists (B) Grant #25871059 to Ryo Kitada.

REFERENCES

[1] (2014). American optometric association website [Online]. Available: http://www.aoa.org

[2] (2014). National center on deaf-blindness website [Online]. Available: http://www.nationaldb.org

[3] (2015). American diabetes association website [Online]. Available: http://www.diabetes.org

[4] Office of Early Childhood Development Virginia Department of Social Services. (2008). Milestones of child development [Online]. Available: http://www.earlychildhood.virginia.gov/documents/milestones.pdf

[5] O. Collignon, G. Dormal, G. Albouy, G. Vandewalle, P. Voos, C. Phillips, and F. Lepore, "Impact of blindness onset on the functional organization and the connectivity of the occipital cortex," *Brain*, vol. 136, no. Pt 9, pp. 1–5, 2013.

[6] H. Mollenkopf, "On the potential of new media and new technologies for old age," in *On the Special Needs of Blind and Low Vision Seniors*, Amsterdam, The Netherlands: IOS Press, 2001, pp. 335–346.

[7] D. N. Saito, T. Okada, M. Honda, Y. Yonekura, and N. Sadato, "Practice makes perfect: The neural substrates of tactile discrimination by mah-jong experts include the primary visual cortex," *BMC Neurosci.*, vol. 7, p. 79, 2006.

[8] (2015). Braille readers are leaders. *Nat. Fed. Blind* [Online]. Available: https://nfb.org/braille-campaign

[9] S. Srinivas and S. C. Hirtle, “The role of affect on expanding indoor spatial knowledge,” in *Indoor Wayfinding and Navigation*, Boca Raton, FL, USA: CRC Press, 2015, pp. 13–34.

[10] D. L. Harkey, D. L. Carter, J. M. Barlow, and B. Billie Louise. (2007). NCHRP web-only document 117A: Accessible pedestrian signals: A guide to best practices [Online]. Available: onlinepubs.trb.org/onlinepubs/nchrp/nchrp_w117a.pdf

[11] P. Bach-Y-Rita, C. Collins, F. Saunders, B. White, and L. Scadden, “Vision substitution by tactile image projection,” *Nature*, vol. 221, pp. 963–964, 1969.

[12] P. Bach-y-Rita and S. W. Kercel, “Sensory substitution and the human-machine interface,” *TRENDS Cognitive Sci.*, vol. 7, no. 12, pp. 541–546, 2003.

[13] J. Brabyn, “New developments in mobility and orientation aids for the blind,” *IEEE Trans. Biomed. Eng.*, vol. BE-29, no. 4, pp. 285–289, Apr. 1982.

[14] J. M. Loomis, R. L. Klatzky, and N. A. Giudice, “Sensory substitution of vision: Importance of perceptual and cognitive processing,” in *Assistive Technology for Blindness and Low Vision*. Boca Raton, FL, USA: CRC Press, 2012.

[15] K. U. Kyung, M. Ahn, D. S. Kwon, and M. A. Srinivasan, “Perceptual and biomechanical frequency response of human skin: Implications for design of tactile displays,” in *Proc. 1st Joint Eurohaptics Conf. Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst.*, 2005, pp. 96–101.

[16] R. W. Van Boven and K. O. Johnson, “The limit of tactile spatial resolution in humans: Grating orientation discrimination on the lip, tongue and finger,” *Neurology*, vol. 44, no. 12, pp. 2361–2366, 1994.

[17] S. Weinstein, “Intensive and extensive aspects of tactile sensitivity as a function of body part, sex and laterality,” in *The Skin Sense*, Springfield, IL, USA: Thomas, 1968, pp. 195–222.

[18] R. W. Van Boven, R. H. Hamilton, T. Kauffman, J. P. Keenan, and A. Pascual-Leone, “Tactile spatial resolution in blind braille readers,” *Neurology*, vol. 54, pp. 2230–2236, 2000.

[19] M. Wong, G. Vishi, and D. Goldreich, “Tactile spatial acuity enhancement in blindness: Evidence for experience-dependent mechanisms,” *J. Neurosci.*, vol. 31, no. 19, pp. 7028–7037, 2011.

[20] A. C. Grant, M. C. Thiagarajah, and K. Sathian, “Tactile perception in blind braille readers: A pscyhophysical study of acuity and hyperacuity using gratings and dot patterns,” *Perception Psychophys.*, vol. 62, no. 2, pp. 301–312, 2000.

[21] J. Loomis, R. Klatkzy, and S. Lederman, “Similarity of tactual and visual picture recognition with limited field of view,” *Perception*, vol. 20, pp. 167–177, 1991.

[22] R. Klatzky, J. Loomis, S. Lederman, H. Wake, and N. Fujita, “Haptic identification of objects and their depictions,” *Perception Psychophys.*, vol. 54, no. 2, pp. 170–178, 1993.

[23] J. P. Warren, L. R. Bobich, M. Santello, and J. D. Sweeney, “Receptive field characteristics under electrotactile stimulation of the fingertip,” *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 16, no. 4, pp. 410–415, Aug. 2008.

[24] S. Kuroki, H. Kajmoto, H. Nii, N. Kawakami, and S. Tachi, “Proposal for tactile sense presentation that combines electrical and mechanical stimulus,” in *Proc. 2nd Joint Eurohaptics Conf. Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst.*, 2007, pp. 121–126.

[25] M. Solomonow, J. Lyman, and A. Freedy, “An initial study on lip perception of electrotactile array stimulation,” *J. Rehabil. Res. Develop.*, vol. 42, no. 5, pp. 705–714, 2005.

[26] T. Maeyama and K. H. Plattig, “Minimal two-point discriminaton in human tongue and palate,” *Amer. J. Otolaryngol.*, vol. 10, no. 5, pp. 342–344, 1989.

[27] H. Kajimoto, Y. Kanno, and S. Tachi, “Forehead retina system,” in *Proc. ACM SIGGRAPH*, 2006, article 11.

[28] P. Bach-y-Rita, K. Kaczmarek, and K. Meier, “The tongue as a man-machine interface: A wireless communication system,” in *Proc. Int. Symp. Inf. Theory Its Appl.*, 1998, pp. 79–81.

[29] C. A. Lozano, K. A. Kaczmarek, and M. Santello, “Electrotactile stimulation on the tongue: Intensity perception, discrimination and cross-modality estimation,” *Somatosensory Motor Res.*, vol. 26, no. 2, pp. 50–63, 2009.

[30] A. Arnoldussen and D. Fletcher, “Visual perception for the blind: The brainport vision device,” *Retinal Physician*, vol. 9, no. 1, pp. 32–34, 2012.

[31] *The PDMA Handbook of New Product Development*, 2nd ed. Hoboken, NJ, USA: Wiley, 2005.

[32] (2015). Universal Design.Com [Online]. Available: http://www.universaldesign.com

[33] J. Brooke. (1986). SUS - A quick and dirty usability scale. Digital Equipment Corporation

[34] F. D. Davis, R. P. Bagozzi, and P. R. Warshaw, “User acceptance of computer technology: A comparison of two theoretical models,” *Manage. Sci.*, vol. 35, no. 8, pp. 982–1003, 1989.

[35] R. A. Cooper, “Introduction,” in *An Introduction to Rehabilitation Engineering*. Boca Raton, FL, USA: CRC Press, 2007, pp. 1–18.

[36] N. Sadato, T. Okada, M. Honda, and Y. Yonekura, “Critical period for cross-modal plasticity in blind humans: A functional MRI Study,” *Neuroimage*, vol. 16, no. 2, pp. 389–400, 2002.

[37] (2014). Size and spacing of braille characters [Online]. Available: www.brailleauthority.org

[38] J. M. Loomis, “On the tangibility of letters and braille,” *Perception Psychophys.*, vol. 29, no. 1, pp. 37–46, 1981.

[39] P. Mousty and P. Bertelson, “Finger movements in braille reading: The effect of local ambiguity,” *Cognition*, vol. 43, no. 1, pp. 67–84, 1992.

[40] P. Bertelson, P. Mousty, and G. D’Alimonte, “A study of braille reading: 2. patterns of hand activity in one-handed and two-handed reading,” *The Quart. J. Exp. Psychol.*, vol. 37A, pp. 235–256, 1985.

[41] S. Millar, “The perceptual ‘Window’ in two-handed braille: Do the left and right hands process text simultaneously?” *Cortex*, vol. 23, pp. 111–122, 1987.

[42] M. A. Heller, “Active and passive tactile braille recognition,” *Bull. Psychonomic Soc.*, vol. 24, no. 3, pp. 201–202, 1986.

[43] N. Sadato, A. Pascual-Leone, J. Grafman, V. Ibanez, M. P. Deiber, G. Dold, and M. Hallett, “Activation of the primary visual cortex by braille reading in blind subjects,” *Nature*, vol. 380, pp. 526–528, 1996.

[44] L. G. Cohen, P. Celnik, A. Pascual-Leone, B. Corwell, L. Falz, J. Dambrosia, M. Honda, N. Sadato, C. Gerloff, M. D. Catala, and M. Hallett, “Functional relevance of cross-modal plasticity in blind humans,” *Nature*, vol. 389, no. 6647, pp. 180–183, 1997.

[45] R. Hamilton, J. P. Keenan, M. Catala, and A. Pascual-Leone, “Alexia for braille following bilaterial occipital stroke in an early blind woman,” *Neuroreport*, vol. 11, no. 2, pp. 237–240, 2000.

[46] A. Bhattacharjee, A. J. Ye, J. A. Lisak, M. G. Vargas, and D. Goldreich, “Vibrotactile masking experiments reveal accelerated somatosensory processing in congenitally blind braille readers,” *J. Neurosci.*, vol. 30, no. 43, pp. 14288–14298, 2010.

[47] H. Burton, R. J. Sinclair, and D. G. McLaren, “Cortical activity to vibrotactile stimulation: An fMRI study in blind and sighted individuals,” *Human Brain Mapping*, vol. 23, no. 4, pp. 210–228, 2004.

[48] P. K. Edman, *Tactile Graphics*, New York: NY. USA: AFB Press, 1992.

[49] M. A. Heller, J. A. Calcaterra, L. L. Burson, and L. A. Tyler, “Tactual picture identification by blind and sighted people: Effects of providing categorical information,” *Perception Psychophys.*, vol. 58, no. 2, pp. 310–323, 1996.

[50] M. A. Heller, “Picture and pattern perception in the sighted and the blind: The advantage of the late blind,” *Perception*, vol. 18, pp. 379–389, 1989.

[51] S. J. Lederman, R. L. Klatzky, C. Chataway, and C. D. Summers, “Visual mediation and the haptic recognition of two-dimensional pictures of common objects,” *Perception Psychophys.*, vol. 47, no. 1, pp. 54–64, 1990.

[52] M. A. Heller, K. Wilson, H. Steffen, and K. Yoneyama, “Superio haptic perceptual selectivity in late-blind and very-low-vision subjects,” *Perception*, vol. 32, pp. 499–511, 2003.

[53] L. J. Thompson, E. P. Chronicle, and A. F. Collins, “Enhancing 2-D tactile picture design from knowledge of 3-D haptic object recognition,” *Eur. Psychologist*, vol. 11, no. 2, pp. 110–118, 2006.

[54] D. Burch and D. Pawluk, “Using multiple contacts with texture-enhanced graphics,” in *Proc. IEEE World Haptics Conf.*, 2011, pp. 287—292.

[55] M. Wijintjes, T. Van Lienen, I. Verstijnen, and A. Kappers, “The influence of picture size on recognition and exploratory behavior in raised-line drawings,” *Perception*, vol. 36, pp. 865–879, 2008.

[56] M. A. Heller, D. D. Brackett, E. Scroggs, H. Steffen, K. Heatherly, and S. Salik, “Tangible pictures: Viewpoint effects and linear perspective in visually impaired people,” *Perception*, vol. 31, pp. 747–769, 2002.

[57] A. Amedi, N. Raz, H. Azulay, R. Malach, and E. Zohary, "Cortical activity during tactile exploration of objects in blind and sighted humans," *Restor Neurol. Neurosci.*, vol. 28, no. 2, pp. 143–156, 2010.

[58] Z. Cattaneo, T. Vecchi, C. Cornoldi, I. Mammarella, D. Bonino, E. Ricciardi, and P. Pietrini, "Imagery and spatial processes in blindness and visual impairment," *Neurosci. Biobehavioral Rev.*, vol. 32, pp. 1346–1360, 2008.

[59] R. G. Long and N. A. Giudice, "Establishing and maintaining orientation for mobility," in *Foundations of Orientation and Mobility*, New York, NY. USA: American Foundation for the Blind, 2010, pp. 45–62.

[60] M. L. Noordzij and A. Postma, "Categorical and metric distance information in mental representations derived from route and survey descriptions," *Psychological Res.*, vol. 69, pp. 221–232, 2005.

[61] B. Roder, F. Rosler, and C. Spence, "Early vision impairs tactile perception in the blind," *Current Biol.*, vol. 14, pp. 121–124, 2004.

[62] C. Thinus-Blanc and F. Gaunet, "Representation of space in blind persons: Vision as a spatial sense?" *Psychological Bull.*, vol. 121, no. 1, pp. 20–42, 1997.

[63] T. Iachini, G. Ruggiero, and F. Ruotolo, "Does blindness affect egocentric and allocentric frames of reference in small and large scale spaces?" *Behavioral Brain Res.*, vol. 273, pp. 73–81, 2014.

[64] J. M. Loomis, R. L. Klatzky, R. G. Golledge, J. G. Cicinelli, J. W. Pellegrino, and P. A. Fry, "Nonvisual navigation by blind and sighted: assessment of path integration ability," *J. Exp. Psychol.: Gen.*, vol. 122, no. 1, pp. 73–91, 1993.

[65] J. J. Rieser, D. A. Guth, and E. W. Hill, "Sensitivity to perspective structure while walking without vision," *Perception*, vol. 15, no. 2, pp. 173–188, 1986.

[66] A. E. Bigelow, "Blind and sighted children's spatial knowledge of their home environment," *Int. J. Behavioral Develop.*, vol. 19, no. 4, pp. 797–816, 1996.

[67] T. Iachini and G. Ruggiero, "The role of visual experience in mental scanning of actual pathways: Evidence from blind and sighted people," *Perception*, vol. 39, pp. 953–969, 2010.

[68] B. Roder and F. Rosler, "Visual input does not facilitate the scanning of spatial images," *J. Mental Imagery*, vol. 22, nos. 3/4, pp. 165–182, 1998.

[69] S. Millar and Z. Al-Attar, "External and body-centered frames of reference in spatial memory: Evidence from touch," *Perception Psychophys.*, vol. 6, no. 1, pp. 51–59, 2004.

[70] A. A. Kalia, G. E. Legge, and N. A. Giudice, "Learning building layouts with non-geometric visual information: The effects of visual impairment and age," *Perception*, vol. 37, pp. 1677–1699, 2008.

[71] R. Kupers, D. R. Chebat, K. H. Madsen, O. B. Paulson, and M. Ptito, "Neural correlates of virtual route recognition in congenital blindness," *Proc. Nat. Acad. Sci.*, vol. 107, no. 28, pp. 12716–12721, 2010.

[72] M. Fortin, P. Voss, C. Lord, J. Pruessner, D. Saint-Amour, C. Rainville, and F. Lepore, "Wayfinding in the blind: Larger hippocampal volume and supranormal spatial navigation," *Brain*, vol. 131, pp. 2995–3005, 2008.

[73] F. McGlone, J. Wessberg, and H. Olausson, "Discriminative and affective touch: Sensing and feeling," *Neuron*, vol. 82, pp. 737–755, 2014.

[74] G. D. Mower, "Perceived intensity of peripheral thermal stimuli is independent of internal body temperature," *J. Comparative Physiological Psychol.*, vol. 90, pp. 1152–5, 1976.

[75] R. Kitada, N. Sadato, and S. J. Lederman, "Tactile perception of nonpainful unpleasantness in relation to perceived roughness: Effects of inter-element spacing and speed of relative motion of rigid 2-d raised-dot patterns at two body loci," *Perception*, vol. 41, pp. 204–220, 2012.

[76] A. D. Craig, "How do you feel? interoception: The sense of the physiological condition of the body," *Nature Rev. Neurosci.*, vol. 3, pp. 655–666, 2002.

[77] A. B. Vallbo, H. Olausson, and J. Wessberg, "Unmyelinated afferents constitute a second system of coding tactile stimuli of the human hairy skin," *J. Neurophysiol.*, vol. 81, pp. 2753–2763, 1999.

[78] L. S. Loken, J. Wessberg, I. Morrison, F. McGlone, and H. Olausson, "Coding of pleasant touch by unmyelinated afferents in humans," *Nature Neurosci.*, vol. 12, pp. 547–548, 2009.

[79] M. Egawa, T. Hirao, and M. Takahashi, "In vivo estimation of stratum corneum thickness from water concentration profiles obtained with raman spectroscopy," *Acta Dermato-venerologica*, vol. 87, pp. 4–8, 2007.

[80] S. J. Lederman and R. L. Klatzky, "Extracting object properties through haptic exploration," *Acta Psychologica*, vol. 84, pp. 29–40, 1993.

[81] S. Lakatos and L. E. Marks, "Haptic form perception: relative salience of local and global features," *Perception Psychophys.*, vol. 61, no. 5, pp. 895–908, 1999.

[82] D. Burch, "Development of a multiple contact haptic display with texture-enhanced graphics," Ph.D. dissertation, Unpublished, 2012.

[83] S. J. Lederman and R. L. Klatzky, "Relative availability of surface and object properties during early haptic processing," *J Exp. Psychol.: Human Perception Perfromance*, vol. 23, no. 6, pp. 1680–1707, 1997.

[84] S. N. Samman and K. M. Stanney, "Multimodal interaction," in *International Encyclopedia of Ergonomics and Human Facts*, vol. 2, 2nd ed. Boca Raton, FL, USA: Taylor & Francis, 2006.

[85] R. Rastogi, "A study towards development of an automated haptic user interface for individuals who are blind or visually impaired," Ph.D. dissertation, Unpublished, 2012.

[86] C. Spence, "Multisensory attention and tactile information-processing," *Behavioral Brain Res.*, vol. 135, pp. 57–64, 2002.

[87] K. Hotting and B. Roder, "Auditory and auditory-tactile processing in congenitally blind humans," *Hearing Res.*, vol. 258, pp. 165–174, 2009.

[88] F. Vidal-Verdu and M. Hafez, "Graphical tactile displays for visually-impaired people," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 15, no. 1, pp. 119–130, Mar. 2007.

[89] S. Choi and K. J. Kuchenbecker, "Vibrotactile display: Perception, technology, and applications," *Proc. IEEE*, vol. 101, no. 9, pp. 2093–2104, Sep. 2013.

[90] A. R. Rut. (1998). Braille readers are leaders [Online]. Available: http://www.ne.nfb.org/node/358

[91] Y. Kato, T. Sekitani, M. Takamiya, M. Doi, K. Asaka, T. Sakurai, and T. Someya, "Sheet-type braille displays by integrating organic field-effect transistors and polymeric actuators," *IEEE Trans. Electron. Dev.*, vol. 54, no. 2, pp. 202–209, Feb. 2007.

[92] X. Wu, S.-H. Kim, H. Zhu, C.-H. Ji, and M. G. Allen, "A refreshable braille cell based on pneumatic microbubble actuators," *J. Microelectromech. Syst.*, vol. 21, no. 4, pp. 908–916, 2012.

[93] M. Takamiya, T. Sekitani, Y. Kato, H. Kawaguchi, T. Someya, and T. Sakurai, "An organic FEDT SRAM with back gate to increase static noise margin and its application to braille sheet display," *IEEE Jo. Solid-State Circuits*, vol. 42, no. 1, pp. 93–100, Jan. 2007.

[94] V. Levesque, J. Pasquero, and V. Hayward, "Braille display by lateral skin deformation with the STReSS2 tactile transducer," in *Proc. World Haptics Conf.*, 2007, pp. 115–120.

[95] J. Roberts, O. Slattery, D. Kardos, and D. Swope, "New technology enables many-fold reduction in the cost of refreshable braille displays," in *Proc 4th Int. ACM Conf. Assistive Technol.*, Arlington, VA, USA, 2000, pp. 42–49.

[96] "Enablemart.com," School health, 2015.

[97] P. C. Headley, V. E. Hribar and D. T. V. Pawluk, "Displaying braille and graphics on a mouse-like tactile display," in *Proc. 13th Int. ACM SIGACCESS Conf. Comput. Accessibility*, Dundee, Scotland, 2011, pp. 235–236.

[98] J. C. Bliss, M. H. Katcher, C. H. Rogers, and R. P. Shepard, "Optical-to-tactile image conversion for the blind," *IEEE Trans. Man-Mach. Syst.*, vol. MMS-11, no. 1, pp. 58–65, Mar. 1970.

[99] Talking Tactile Tablet. (2015) [Online]. Available: http://touchgraphics.com/portfolio/ttt/

[100] C. M. Baker, L. R. Milne, J. Scofield, C. L. Bennett, and R. E. Ladner, "Tactile graphics with a voice: Using QR codes to access text in tactile graphics," in *Proc. 16th Int. ACM SIGACCESS Conf. Comput. Accessibility*, Rochester, NY, USA, 2014, pp. 75–82.

[101] S. K. Kane, M. Ringel Morris, and J. O. Wobbrock, "Touchplates: Low-cost tactile overlays for visually impaired touch screen users," presented at the *15th Int. ACM SIGACCESS Conf. Computers and Accessibility*, Bellevue, WA, USA, vol. 8, 2013.

[102] N. Giudiice, H. P. Palani, E. Brenner, and K. M. Kramer, "Learning non-visual graphical information using a touch-based vibro-audio interface," in Proc. 14th Int. ACM SIGACCESS Conf. Comput. Accessibility, Boulder, CO, USA, 2012, pp. 103–110.

[103] C. Xu, A. Israr, I. Poupyrev, O. Bau, and C. Harrison, "Tactile display for the visually impaired using teslaTouch," in *Proc. Human Factors Comput. Syst.*, Vancouver, BC, Canada, 2011, pp. 317–322.

[104] R. Rastogi, D. Pawluk, and J. M. Ketchum, "Issues of using tactile mice by individuals who are blind and visually impaired," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 18, no. 3, pp. 311–318, Jun. 2010.

[105] V. Levesque and V. Hayward, "Tactile graphics rendering using three laterotactile drawing primitives," in *Proc. IEEE Haptics Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst.*, Reno, NV, USA, 2008, pp. 429–436.

[106] P. C. Headley and D. T. V. Pawluk, "A low-cost, variable-amplitude haptic distributed display for persons who are blind and visually impaired," in *Proc. 12th Int. ACM SIGACCESS Conf. Comput. Accessibility*, 2010, pp. 227–228.

[107] L. Brayda and C. Campus, "Conveying perceptible virtual tactile maps with a minimalist sensory substitution device," in *Proc. IEEE Int. Workshop Haptic Audio Visual Environments. Games*, 2012, pp. 7–12.

[108] T. Pietrzak, A. Crossan, S. A. Brewster, B. Martin, and I. Pecci, "Creating usable pin array tactons for nonvisual information," *IEEE Trans. Haptics*, vol. 2, no. 2, pp. 61–72, Apr.–Jun. 2009.

[109] S. Walker and J. K. Salisbury, "Large haptic topographic maps: marsview and the proxy graph algorithm," in *Proc. Symp. Interactive 3D Graph.*, 2003, pp. 83–92.

[110] C. Magnuson and K. Rassmus-Grohn, "Non-visual zoom and scrolling operations in a virtual haptic environment," presented at the *3rd Int. Conf. Eurohaptics*, Dublin, Ireland, 2003.

[111] M. Ziat, O. Gapenne, J. Stewqart, C. Lenay, and J. Bausse, "Design of haptic zoom: Levels and steps," in *Proc. 2nd Joint Eurohaptics Conf. Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst.*, 2007, pp. 102–108.

[112] R. Rastogi and D. Pawluk, "Intuitive tactile zooming for graphics accessed by individuals who are blind and visually impaired," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 21, no. 4, pp. 655–663, Jul. 2013.

[113] R. Rastogi and D. Pawluk, "Tactile diagram simplification on refreshable displays," *Assistive Technol.*, vol. 25, no. 1, pp. 31–38, 2013.

[114] V. Levesque, G. Petit, A. Dufresne, and V. Hayward, "Adaptive level of detail in dynamic, refreshable tactile graphics," in *Proc. IEEE Haptics Symp.*, Vancouver, BC, Canada, 2012, pp. 1–5.

[115] S. Paneels and J. C. Roberts, "Review of designs for haptic data visualization," *IEEE Trans. Haptics*, vol. 3, no. 2, pp. 119–137, Apr.–Jun. 2010.

[116] K. Moustakas, N. Georgios, K. Konstantinos, D. Tzovaras, and M. G. Strintzis, "Haptic rendering of visual data for the visually impaired," *IEEE Multimedia*, vol. 14, no. 1, pp. 62–72, Jan.–Mar. 2007.

[117] J. P. Fritz and K. E. Barner, "Design of a haptic data visualization system for people with visual impairments," *IEEE Trans. Rehabil. Eng.*, vol. 7, no. 3, pp. 372–384, Sep. 1999.

[118] W. Yu and S. A. Brewster, "Evaluation of multimodal graphs for blind people," *J. Universal Access Inf. Soc.*, vol. 2, no. 2, pp. 105–124, 2003.

[119] R. Long and E. Hill, "Establishing and maintaining orientation and mobility," in *Foundations of Orientation and Mobility*, 2nd ed., B. Blasch, W. Wiener, and R. Welsh, Eds. New York, NY, USA: AFB Press, 1997.

[120] N. Giudice and G. Legge, "Blind navigation and the role of technology," in *Engineering Handbook of Smart Technology for Aging, Disability, and Independence*, A. Helal, M. Mokhtari, and B. Abdulrazak, Eds. Hoboken, NJ, USA: Wiley, 2008, pp. 479–500.

[121] C. Wickens, "Processing resources in attention," in *Varieties in Attention*, R. Parasuraman and D. Davis, Eds. London, U.K.: Academic, 1984, p. 63–102.

[122] Sense navigation GPS [Online]. Available: http://www.senderogroup.com/products/shopvsnav.htm, 2015.

[123] J. R. Marston, J. M. Loomis, R. L. Klatzky, and R. G. Golledge, "Nonvisual route following with guidance from a simple haptic or auditory display," *J. Visual Impairment Blindness*, vol. 101, pp. 203–211, Apr. 2007.

[124] M. Altini, E. Farella, E. Pirini, and L. Benini, "A cost-effective indoor vibro-tactile navigation system for blind people," in *Proc. Int. Conf. Health Informat.*, Rome, Italy, 2011, pp. 477–481.

[125] S. Bosman, B. Groenendaal, J. Findlater, T. Visser, M. De Graaf, and P. Markopoulos, "GentleGuide: An exploration of haptic output for indoors pedestrian guidance," in *Proc. Mobile HCI*, Udine, Italy, 2003, pp. 358–362.

[126] J. Van Erp, A. Hendrik, V. Veen, and C. Jansen, "Waypoint navigation with a vibrotactile waist belt," *ACM Trans. Appl. Perception*, vol. 2, no. 2, p. 106–117, 2005.

[127] J. Van Erp, "Presenting directions with a vibro-tactile torso display," *Ergonomics*, vol. 48, no. 3, pp. 302–313, 2005.

[128] A. Cosgun, E. Sisbot, and H. Christensen, "Evaluation of rotational and directional vibration patterns on a tactile belt for guiding visually impaired people," in *Proc. IEEE Haptics Symp.*, Houston, TX, USA, 2014, pp. 367–370.

[129] A. A. Kalia, G. E. Legge, R. Roy, and A. Ogale, "Assessment of indoor route-finding technology for people who are visually impaired," *J. Visual Impairment Blindness*, vol. 104, pp. 135–147, 2010.

[130] (2011). *Sendero GPS LookAround* [Online]. Available: https://www.senderogroup.com/support/supportandroid.htm

[131] N. A. Giudice, L. A. Walton, and M. Worboys, "The informatics of indoor and outdoor space: A research agenda," in *Proc. 2nd ACM SIGSPATIAL Int. Workshop Indoor Spatial Awareness*, San Jose, CA, USA, 2010, pp. 47–53.

[132] B. Poppinga, C. Magnusson, M. Pielot, and K. Rassmus-Grohn, "TouchOver map: Audio-tactile exploration of interactive maps," in *Proc. ACM 13th Int. Conf. Human Comput. Interaction Mobile Dev. Services*, New York, NY, USA, 2011, pp. 545–550.

[133] R. L. Klatzky, N. A. Giudice, C. R. Bennet, and J. M. Loomis, "Touch-screen technology for the dynamic display of 2d spatial information without vision: Promise and progress," *Multisensory Res.*, vol. 27, pp. 359–378, 2014.

[134] S. J. La Grow and R. G. Long, *Orientation and Mobility: Techniques for Independence*. Alexandria, Egypt: AERBVI, 2011.

[135] J. Cutter, *Independent Movement and Travel in Blind Children: A Promotion Model*. Charlotte, NC, USA: Inf. Age Publishing, 2007.

[136] D. Dakopoulos and N. G. Bourbakis, "Wearable obstacle avoidance electronic travel aids for blind: A survey," *IEEE Trans. Syst., Man, Cybern. C, Appl. Rev.*, vol. 40, no. 1, pp. 25–35, Jan. 2010.

[137] L. Russell, "Travel path sounder," presented at the *Rotterdam Mobility Res. Conf.*, New York, NY, USA, 1965.

[138] N. Pressey, "Mowat sensor," *Focus*, vol. 11, no. 3, pp. 35–39, 1977.

[139] Y. Wang and K. J. Kuchenbecker, "HALO: Haptic alerts for low-hanging obstacles in white cane navigation," in *Proc. IEEE Haptics Symp.*, 2012, pp. 527–532.

[140] W. Penrod, M. Corbett, and B. Blasch, "A master trainer class for professionals in teaching the ultracane electronic travel device," *J. Visual Impairment Blindness*, vol. 99, no. 1, pp. 711–714, 2005.

[141] J. Borenstein and I. Ulrich, "The guidecane—A computerized travel aid for the active guidance of blind pedestrians," in *Proc. IEEE Int. Conf. Robot. Autom.*, Albuquerque, NM, USA, 1997, vol. 2, pp. 1283–1288.

[142] I. Ulrich and J. Borenstein, "The guidecane - applying mobile robot technologies to assist the visually impaired," *IEEE Trans. Syst., Man, Cybern. A, Syst., Humans*, vol. 31, no. 2, pp. 131–136, Mar. 2001.

[143] S. Gallo, D. Chapuis, L. Santos-Carreras, Y. Kim, P. Retornaz, H. Bleuler, and R. Gassert, "Augmented white cane with multimodal haptic feedback," in *Proc. 3rd IEEE RAS EMBS Int. Conf. Biomed. Robot. Biomechatronics*, Tokyo, Japan, 2010, pp. 149–155.

[144] W. M. Jenkins, M. M. Merzenich, M. T. Ochs, T. Allard, and E. Guic-Robles, "Functional reorganization of primary somatosensory cortex in adult owl monkeys after behaviorally controlled tactile stimulation," *J. Neurophysiol.*, vol. 63, no. 1, pp. 82–104, 1990.

[145] A. Bubic, E. Striem-Amit, and A. Amedi, "Large-scale brain plasticity following blindness and the use of sensory substitution devices," in *Multisensory Object Perception in the Primate Brain*, New York, NY, USA: Springer Science+Business Media, 2010, pp. 351–380.

[146] "Braille - what is it? what does it mean to the blind?" *Future Reflections*, vol. 1, no. 15, 1996.

[147] T. L. Varao Sousa, J. S. Carriere, and D. Smilek, "The way we encounter reading material influences how frequently we mind wander," *Frontiers Psychol.*, vol. 4, p. 892, 2013.

[148] S. Millar, *Reading By Touch*. New York, NY, USA: Routledge, 1997.

[149] J. M. Loomis and S. J. Lederman, "Tactual perception," in *Handbook of Perception and Human Performance*. New York, N.Y., USA: Wiley, 1986.

[150] J. M. Loomis, "An investigation of tactile hyperacuity," *Sensory Processes*, vol. 3, pp. 289–302, 1979.

[151] J. M. Wolfe, *Sensation and Perception*. Sunderland, MA, USA: Sinauer Assoc., 2015.

Dianne T.V. Pawluk received the PhD degree from Harvard. She is an associate professor of biomedical engineering at Virginia Commonwealth University. She teaches courses in the areas of computational methods, assistive technology, and rehabilitation engineering. Her active research areas include the development of haptic assistive devices and methods for individuals who are blind or visually impaired, including devices and algorithms for tactile graphics, orientation and mobility, haptic perceptual organization, and the effective use of multimodal presentations in education. She currently serves as an associate editor for the *IEEE Transactions on Haptics*. She is a member of the IEEE.

Richard J. Adams received the BS degree as a distinguished graduate from the U.S. Air Force (USAF) Academy in 1989, the MS degree from the University of Washington in 1990, and the PhD degree from the University of Washington in 1999. He served as an active duty commissioned officer in the USAF between 1989 and 2009. He returned to the USAF Academy in 2007 as an assistant professor in the Department of Astronautical Engineering. In 2009, he retired from the Air Force and joined Barron Associates, Inc., where, as a principal research scientist, he currently leads multiple efforts spanning game-based rehabilitation systems, assistive technology for the blind and visually impaired, tactile human-computer interfaces, and spaceborne sensors. He is a senior member of the IEEE.

Ryo Kitada received the PhD degree from Kyoto University. He is an assistant professor in the Division of Cerebral Integration, National Institute for Physiological Sciences, Okazaki, Japan. His research interests include human tactile/haptic perception, cognition, and neuroscience.

▷ **For more information on this or any other computing topic, please visit our Digital Library at** www.computer.org/publications/dlib.