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Sensory substitution of vision: Importance of perceptual and cognitive processing

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Introduction

For most activities of daily life, vision is the preeminent sense for humans. Over one million optic nerve fibers of each eye transfer vast amounts of information to the brain every second, and a large fraction of the cortex is involved in the processing of this information. The most obvious effect of losing vision is a significant decrement in performance of actions that rely on the spatial resolution and wide field of view that vision provides, particularly under tight temporal constraints (see Chapter 2 and 4). Returning a tennis serve or driving in city traffic are examples. Nonetheless, the ability of many blind people to perform tasks that we generally think of as visually guided, like steering a bicycle around obstacles (using echolocation), is testimony to the potential of other sources of information to substitute for visual input. This form of sensory substitution, allowing one or more of the remaining spatial senses to take the place of vision, is possible because hearing and touch are also informative about the environment. Expanding these natural sensory substitutions with compensatory strategies and theoretically-motivated technologies would no doubt enhance the capabilities of blind and low-vision individuals.

Over the past two centuries, inventions have come into use that augment the natural substitution of one sense by another. Braille provides access to text, and the long cane supplements spatial hearing in the sensing of obstacles, borders between surfaces underfoot, etc. Over the last five decades, electronic devices, many based on computers, have emerged as more effective ways of promoting vision substitution (see the edited volume by Warren et al., 1985 for a good introduction and Giudice et al., 2008 and Levesque, 2009 for recent reviews). Access to text has greatly expanded with electronic Braille displays and synthetic speech. For obstacle avoidance and sensing of the local environment, a number of ultrasonic sensors have been developed that use either auditory or tactile displays (Brabyn 1985; Collins 1985; Kay 1985; see also Chapter 3). For navigation through the larger-scale environment, assistive technologies now include GPS-based navigation systems (Chapter 5) and remote infrared audible signage (Chapter 6).

In the remainder of this chapter, we examine the potential for new technologies to assist blind people by substituting for information that is otherwise visually encoded. We do so through the lens of cognitive science and neuroscience, which leads to an understanding of the information processing capabilities of individuals with and without sight. Our over-arching message is that while great potential for sensory substitution exists, there are clear constraints on the utility of new technologies that stem from perceptual and cognitive processing. Unfortunately, these constraints have neither been widely recognized nor their implications understood by researchers in the field. Besides discussing these constraints, we will offer examples of effective assistive technology and suggest guidelines for the development of future devices. The organization of the chapter is as follows: In the first section of the chapter, we begin with a distinction between general-purpose and special-purpose sensory substitution, which obviously differ in the range of activities they are intended to support. To aid in evaluating these approaches, we present a general theoretical framework for sensory substitution that relies on knowledge about perceptual and cognitive information processing. We then consider different bases for sensory substitution, ranging from functional equivalence and brain plasticity to artificial intelligence. After a brief section on the implications of differences between blind and sighted people for sensory substitution, we end with some recommendations for the design process.

General-Purpose and Special-Purpose Sensory Substitution

An approach that has been tried in the past is general-purpose substitution of vision by touch. This is perhaps best exemplified by the pioneering work of Paul Bach-y-Rita and Carter Collins (Bach-y-Rita, 1967, 1972, Collins, 1970), who used a video camera to drive a tactile display of vibrotactile or electrotactile stimulators. Each 2-D visual image is represented by an isomorphic tactile image on some surface of the body, such as the back or abdomen. The premise behind such an approach is that with sufficient practice, people will eventually be able to interpret the tactile stimulation well enough to perform many activities that would otherwise be extremely challenging, if not impossible. The early research offered tantalizing evidence of success with simple tasks (Bach-y-Rita, 1972). In addition, the early research (e.g., White, 1970; White et al., 1970) provided fascinating results that led to a great deal of subsequent interest by scientists and philosophers in what has been termed “distal attribution” (e.g., Auvray et al., 2005; 2009b; Epstein et al., 1986; Loomis, 1992; O'Regan et al., 2001; Siegle et al., 2010). Distal attribution (or externalization) refers to experiencing tactile stimulation on the skin surface as objects external to the user. This occurs when the user is allowed to manipulate the video camera and observe the contingencies between motor activity and the resulting changes in tactile stimulation. Importantly, distal attribution can be obtained with just a single tactile stimulator (Siegle et al.,, 2010). Besides the research on distal attribution, investigation of performance on spatial tasks has continued be done by Bach-y-Rita and his colleagues as well as by others (e.g., Bach-y-Rita, 2004; Bach-y-Rita et al., 2003; Chebat et al., 2011; Sampiao et al. 2001; Segond et al., 2005). Despite the many years of research, no general-purpose vision-to-touch translator has emerged that is sufficiently robust and reliable for use in everyday life. The same can be said for projects pursuing the goal of general sensory substitution of vision using audition (e.g., Auvray et al., 2009a; Capelle et al., 1998; Meijer, 1992; Veraart, 1989).

In light of the failure of general-purpose vision substitution for use in everyday life, efforts today are more commonly directed toward the creation of special-purpose devices that enable specific activities such as pattern identification, perception of spatial layout, control of locomotion with respect to the near environment (mobility), and navigation through the large-scale environment (orientation and wayfinding). Small-scale successes have been demonstrated for some simple tasks like walking around obstacles (e.g., Auvray et al., 2009a; Chebat et al., 2011; Collins, 1985; Jansson, 1983; Segond et al., 2005). Unfortunately, too many researchers developing sensory substitution devices, while touting the fascinating work on distal attribution and encouraged by good performance on simple tasks, have neglected the basic science on perceptual and cognitive processing in the design and evaluation of their devices. In the following section, we indicate how the ultimate success of any device for substitution across perceptual channels fundamentally depends on how the required information is matched to the capabilities of the human perceptual-cognitive system.

A Theoretical Framework for Special-Purpose Sensory Substitution

Any effort to compensate for the absence of vision by substituting another information channel comes down to the use of touch or hearing, the other spatially informative senses. Extending earlier theoretical work (Collins, 1985; Kaczmarek, 2000; Loomis, 2003; Loomis et al, 2007; Veraart, 1989; Veraart et al., 1985), we propose that a principled approach to using touch or hearing as a substitute for vision in connection with a particular function comprises two essential steps. The first is to identify the optical, acoustic, or other type of information (e.g., ultrasound) that is most effective in enabling that function. The second step is to determine how to display this information to the remaining spatial senses of touch and hearing. Besides the use of direct spatial cues, display methods include using spatial language that is presented, for example, through synthetic speech or electronic Braille.

Step 1: Identifying Informational Requirements for a Task

The first step, then, requires research to identify what information is necessary to perform the function. As an example, consider obstacle avoidance while walking. Usually, a person walking through a cluttered environment with adequate lighting is able to use vision to avoid collision with obstacles. Precisely what information sensed using vision, ultrasound, radar, laser range finding, or some combination thereof, best affords obstacle avoidance? One way to address this question is purely experimental – in the case of visual information alone, degrade a person's vision by limiting the field of view and spatial resolution to learn the minimum amount of visual information that affords a desired walking speed and accuracy. Cha et al. (1992) performed such an analysis using pixelized displays to determine the fewest number of points in a square matrix needed for effective travel through an environment containing obstacles. An alternative approach is strictly theoretical: given some form of reflecting energy (e.g., light, radar, or ultrasound) and a corresponding receiver, use computational modeling to determine the least information required by an ideal observer to perform the task.

Regrettably, there has been little research of either kind on the informational requirements of visually based behaviors. Without this research base, the motivation for design and development of sensory substitution devices, or assistive technology more generally, has unfortunately often been ad hoc. Even when relevant research is available, it has sometimes been overlooked in the face of attractive (read: "sexy") new technology or engineering design.

Step 2: Coupling Task Information with the Substituting Modalities

The second step in designing a sensory substitution system is to couple the critical environmental information with the substituting modality or modalities (touch and audition). This coupling involves two different factors: sensory bandwidths of the afferent pathways of the source and substituting modalities and the nature of higher-level processing. Vision, hearing, and touch each can be characterized by their sensory bandwidth, which refers to the rate at which information from the peripheral sense organs can be transmitted via the afferent pathways to the brain.

The sensory bandwidth for vision has two components, spatial bandwidth and temporal bandwidth. The spatial bandwidth is the product of (1) the total number of resolvable pixels in each eye, which in turn is determined by the total field of view and the visual acuity at each retinal position, and (2) the number of noticeably different levels of brightness and color at each pixel. The temporal bandwidth refers to the rate of information processing for each pixel. The components of sensory bandwidth for vision have been investigated extensively using psychophysics (e.g., Olzak et al., 1986; Watson, 1986; Winkler, 2005). The spatial bandwidth component is closely related to the number of optic nerve fibers from each eye. Because the spatial bandwidth of vision is far greater than that of the other two senses, attempting to use some isomorphic spatial mapping from a video camera into the spatial dimensions of touch or hearing inevitably means a huge loss of information. To support this claim in connection with touch, we describe some research by the first author comparing the spatial bandwidths of vision and touch, work that was aimed at understanding why tactile sensory substitution of vision met with limited success. In a number of studies, he showed functional equivalence between tactile pattern perception and blurred vision, in which blurring (low-pass spatial filtering) was used to reduce the spatial resolution of vision (relative to pattern size) down to the level of touch. Some of the studies were done using an early version of the Tactile Vision Substitution System developed by Bach-y-Rita and Collins (Bach-y-Rita, 1967, 1972; Collins, 1970). The particular system used had a 20 x 20 array of vibrotactile stimulators placed across the back. The system included a 20 x 20 array of lamps that were illuminated when the corresponding vibrotactors were activated. In two separate studies on letter recognition (Apkarian-Stielau et al., 1975; Loomis et al., 1976), it was found to be necessary to drastically blur the visual display in order to bring letter recognition performance for vision down to that of touch; indeed, the diameter of the subjective blur circle associated with each illuminated bulb was wider than the visual display (Apkarian-Stielau et al., 1975). These two experiments indicated that much of the spatial information within the tactile display was being eliminated by the intrinsic spatial filtering of the cutaneous system and thus not reaching the processing stages involved in recognition. More refined research was done later using raised characters, including letters and Braille, on the fingertips, along with low-pass spatial filtering of the corresponding visual characters (Loomis, 1981, 1982, 1990; Loomis et al., 1986). This work made it clear that much of the spatial information in patterns covering the fingertip is filtered out in cutaneous processing (see Figure 8.1).

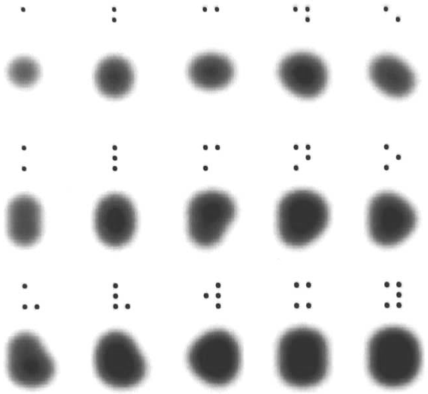

Figure 1. Depiction of how braille characters are low-pass filtered during cutaneous processing. The visually blurred versions here are recognized with about the same level of accuracy (75%) as the alphabetic braille characters presented to the finger pad of the index finger (Loomis, 1981; see also Loomis, 1982, 1990). Much of the internal spatial detail is filtered out, but variation in shape allows good recognition performance by someone familiar with braille. (Only a subset of the alphabetic characters is depicted. In the experiments cited, the tactile characters were slightly larger and more elevated than braille characters used for actual reading.)

Because of the limited spatial resolution of cutaneous processing, the number of resolvable pixels for any circumscribed region is orders of magnitude smaller than the corresponding number for vision. Here we provide a comparison between vision and the distal pad of the index finger. The binocular field subtends 200° x 130° (Harrington, 1971). Using estimates of visual resolution as a function of eccentricity out to 30° (Wertheim,1894; reprinted in Westheimer, 1987) and extrapolating the best fitting curve out to 65°, a conservative lower bound for vision is about 700,000 resolvable points for the central 65° of vision. In contrast, an upper bound for the distal pad of the index finger is just 330 resolvable points, assuming a spatial resolution of 1.2 mm (Legge et al., 2008). Consequently, the spatial bandwidth of the four fingertips (thumb excluded) would still be more than 500 times lower than that of vision. To convey a sense of how impoverished is the information being transmitted by the fingers, Figure 8.2, panel B, depicts the spatial information sensed by the four fingers using the functional equivalence of touch and blurred vision (Loomis, 1981, 1982).

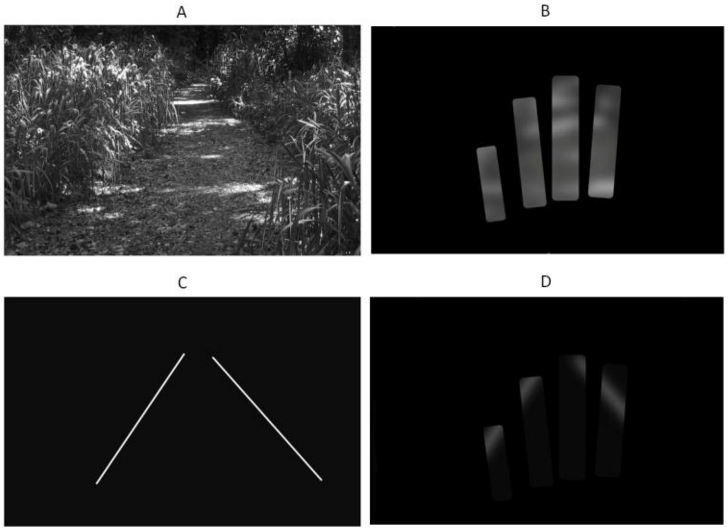

Figure 8.2 about here

Figure 2. A. An outdoor scene with a path. B. Using the analogy between touch and blurred vision (Loomis, 1981, 1982), the scene is viewed through apertures representing four of the fingers with low-pass spatial filtering that is approximately that of the fingers. In reality, the fingers would scan the tactile facsimile of the path and pick up task-relevant information. Even so, at any one instant, the variations in intensity would convey little information about the path for this scene. C. A scene limited to high contrast lines representing the edges of the path in A. D. The high contrast scene viewed through apertures representing four of the fingers under the same field restriction and filtering as in B. Now, the variations in intensity are quite informative about the edges of the path despite the same degree of field restriction and filtering.

Much less research has been done on the spatial bandwidth of spatial hearing (see Blauert, 1997 for a review of spatial hearing in general). The parameters specifying the location of a sound source are distance, azimuth, and elevation. Most research that bears on spatial bandwidth has been done using tasks in which a sound source is successively presented in two locations. The resulting measure of discrimination is much finer than the measure of spatial resolution, which would involve spatially separating two identical sources until the two can be perceived as distinct (Loomis, 1979). Even so, measures of discrimination indicate poor precision along each of the three spatial dimensions (Ashmead et al., 1990; Blauert, 1997; Perrott et al., 1990, Strybel et al., 1984), making spatial hearing a poor candidate for sensory substitution based on spatial isomorphism. Accordingly, few researchers have attempted to convey information about 2-D spatial patterns using any pair of these auditory dimensions (for one who did, see Hollander, 1994). The more common approach, as will be discussed later, is to use azimuth or the passage of time to represent the horizontal axis of a figure and pitch to represent the vertical axis (Auvray et al., 2005; Cronly-Dillon et al., 2000; Kramer, 1994; Meijer, 1992).

Because the informational requirements of different tasks vary dramatically, some tasks will be possible using the spatial isomorphism of hearing or touch to substitute for vision, others not. Steering toward a point of light in a dark room requires very little spatial information; indeed, aiming a single photocell toward the point of light is sufficient. Thus, such a task is a good candidate for auditory or tactile substitution of vision. In connection with haptic touch, Lenay et al. (1997) have shown that a single photocell on the finger that activates a vibrotactile stimulator affords steering toward a point. Slightly more complex locomotion tasks, such as walking through a field of high contrast obstacles, have also been shown to be feasible (e.g., auditory: Auvray et al., 2009a; tactile: Chebat et al., 2011; Collins, 1985; Jansson, 1983). Panels C and D of Figure 8.2 show how high-contrast information relevant to task performance can afford successful mobility in spite of the spatial bandwidth limitations of touch. At the other extreme of informational requirements is normal driving in a city environment with lots of cars and pedestrian traffic. Here, the required information is immense, insuring that sensory substitution based on isomorphic mapping of raw visual data from a video camera onto the spatial dimensions of hearing or touch will fail (Collins, 1985).

In addition to sensory bandwidth, of which spatial bandwidth is the most limiting component, the other factor placing limits on the effectiveness of certain assistive technologies is the nature of higher-level processing for vision, hearing, and touch. For example, the fact that visual display of the acoustic speech signal (e.g, the speech spectrogram) has yet to lead to successful visual substitution of speech, despite the higher sensory bandwidth of vision, indicates that vision does not have access to specialized speech processing associated with hearing (Zue et al., 1979). Similarly, research suggests differences in higher level processing of vision and touch in connection with the perception of 3-D objects and their depictions. Illustrating this is the challenge of using the sense of touch to recognize raised pictures of common objects (for review, see Wijntjes et al., 2008a). A study by Loomis et al. (1991) points to one of the reasons for the poor performance. They compared haptic recognition of raised pictures with visual recognition of the same pictures viewed on a computer display. In the haptic condition, observers felt raised pictures with one finger or two adjacent fingers, while in the visual condition, observers moved a stylus over a touch tablet to sequentially reveal portions of the picture on a stationary aperture on the display. The visual aperture was equivalent in "field of view" to the sensing surface of the one or two fingers. In addition, the computer display was optically blurred to reduce visual spatial resolution to that of touch. Recognition performance was nearly the same for vision and touch for the “one finger” condition (about 47% correct with 95 sec response latency). Doubling the field of view produced a dramatic increase in performance for vision (80% correct with 60 sec latency) but only a very modest increase for touch. For unrestricted field of view (no aperture), visual performance was 100% with 1.3 sec latency. In another study, Klatzky et al. (1993) found that feeling raised pictures with five fingers instead of one improved performance about the same as doubling the visual field of view in the earlier study. Besides confirming the results of other studies showing poor haptic recognition of pictures of common objects, these two studies indicate that the effective haptic field of view increases more slowly with physical field of view than does the effective visual field of view (see also Craig, 1985). This means that the impoverished scene information depicted in Figure 8.2, panel B, for visual apertures overestimates what is actually available with haptic sensing. A possible reason for this smaller effective field of view is that working memory, which is involved in the integration of sequentially presented information over space and time, has lower capacity for touch than for vision (Gallace et. al, 2008). Another likely reason that haptic recognition of pictures falls short of visual recognition of pictures is that the figural processing associated with visual perception is less accessible by touch (Wijntjes et al., 2008b). This is almost surely the case for congenitally blind observers, who perform worse than adventitiously blind observers (Kennedy et al., 1977; Heller, 1989; Lederman et al., 1990).

Still another example of differences in high level processing between touch and vision comes from research on the recognition of 3-D objects. Newell et al. (2001) had participants learn the shapes of objects either by visual or haptic exploration, during which all surfaces of the objects were perceived. The recognition phase was performed with the same or different modality, and the objects were in their original orientations or reversed orientations. The results indicated that vision preferentially encodes the front surfaces of objects during learning; whereas, touch preferentially encodes the back surfaces.

The focus so far has been on spatially isomorphic sensory substitution, but many of the successes in sensory substitution and assistive technology, as detailed in this volume, make use of technology that is not spatially isomorphic. Foremost is speech synthesis that can deliver linguistic information in the form of environmental labels, spatial descriptions of the environment, or commands to the user. GPS-based navigation systems for blind people offer the best examples (Chapter 5). In some versions, the linguistic information is supplemented by perceptual information about environmental location using virtual sound or haptics (Klatzky et al., 2006; Loomis et al., 2005). A primary reason that GPS navigation systems have been so successful is that GPS technology provides the user with access to information critical for navigation without overwhelming the user with irrelevant information. Other examples of effective assistive devices are those using ultrasonic sensors to aid in obstacle avoidance (Kay, 1985; for a recent summary see Giudice et al., 2008). Although these devices have not been widely adopted, a blind person learning to use such devices can reliably avoid obstacles because they provide the essential information for obstacle avoidance while excluding extraneous information that serves only to confuse.

In this section we have presented the two essential steps in developing sensory substitution devices. The first, identifying the required information for a function, is too often ignored by researchers and developers. Even if not, relevant research may be lacking, requiring that the developer of a new system do preliminary testing. The second step, effectively coupling the required information to the user, is too often given insufficient consideration. Even if the requisite information can be translated into appropriate stimulation for the substituting modality, there are perceptual and cognitive processing limitations that might stand in the way of successful sensory substitution. With these considerations in mind, we discuss a number of bases for implementing successful sensory substitution.

Bases for Sensory Substitution

The general goal of sensory substitution is to allow functionality associated with one modality to be provided by another. The ideal would be to produce comparability of function. If inputs from two sensory channels lead to matching behavioral performance in some task, we say that at least for purposes of that task, the channels demonstrate *functional equivalence.* For some tasks, quite different representations such as object names and visual depictions can produce equivalent performance. Generally, sensory substitution falls short of this goal.

There are multiple bases by which touch, hearing, and language might singly or jointly lead to substitutability with vision. Building on what is known so far, we can identify some of these bases, which we discuss in this section. They are not exclusive of one another, and effective sensory substitution for a given activity (e.g. navigation) is likely to rely on more than one. Cattaneo and Vecchi (2011) provide an excellent review of research relating to some of these potential bases.

Functional Equivalence through Spatial Isomorphism

Spatial isomorphism between representations from two modalities ensures that parameters extracted from one will match those of the other, without systematic bias. While spatial isomorphism of representations certainly supports equivalence of function, it is not by itself sufficient. An additional key requirement is the existence of processes that can operate on the spatial parameters of the isomorphic representations so as to produce comparable performance. Under the assumption that this requirement is met, spatial isomorphism has been one of the most prevalent bases proposed for sensory substitution.

This leads to the question of whether spatial representations achieved by vision and other modalities are, to at least an approximate degree, isomorphic. We say approximate, because differences in spatial bandwidth and working memory limitations must be taken into account. Consider first the sense of touch, as the greatest amount of work on spatial isomorphism has concerned touch/vision correspondence. Some studies do suggest that the visual and haptic channels, after adjusting for differences in the processing limitations of touch, produce isomorphic representations of simple 2-D and 3-D shapes (Klatzky et al. 1993; Lakatos et al.,1999; Loomis, 1981; 1982; 1990; Loomis et al. 1991).

Work of the present authors provides evidence for isomorphism between vision and other modalities with respect to the spatial layout of multiple objects relative to the observer. These studies demonstrate comparable performance after encoding spatial layout from different modalities vision, hearing, or spatial language. Equivalence was found for vision and touch, for example, in a task of spatial updating of self-position in the absence of visual feedback (Klatzky et al., 2003); importantly, the targets were matched for their encoded (as opposed to physical) locations, by placing each visual target at the perceptual distance of the corresponding auditory target. Comparable performance has also been found for judgments of relative direction (pointing to a target from the perspective of another) for maps encoded through vision or touch (Giudice et al., 2011), and across multiple spatial targets encoded by vision and spatial language (Avramides et al., 2004).

To the extent that spatial isomorphism exists, within the constraints of differential processing limitations, touch should be able to substitute for vision in tasks that take spatial parameters such as distance and direction as inputs. One such task is cross-modal integration, where information about the same spatial magnitude, potentially with a discrepancy, is provided to multiple senses, and a jointly determined estimate must be achieved (Ernst et al. 2001; Heller et al. 1999, Rock et al., 1964). In a seminal paper, Ernst and Banks (2002) tested a maximum-likelihood model for integration of information about the size of a step-edge conveyed by vision and touch. The model assumes that the two channels combine their perceptual outputs by means of a weighted average, where the weight corresponds to the reliability (inverse variability) of the channel. The results indicated that metrically appropriate spatial information was provided by both channels, but with substantially less reliability for touch than for vision. This finding is in keeping with earlier proposals that spatial processing is less "modality-appropriate" for touch than vision (Welch et al., 1980).

Another paradigm for assessing the consequences of spatial isomorphism is cross-modal matching, a task where an object is first sensed by touch and then identified by vision, or vice versa. A substantial literature on this topic indicates that cross-modal matching across vision and touch can be achieved with accuracy well above chance (Abravanel 1971; Newell et al., 2001; Phillips et al. 2009). Performance in the cross-modal case does not generally exceed the level of unimodal matching achieved by the lesser modality. However, gains from using a second modality may be found when one sense guides the other to otherwise unavailable or ambiguous information (Phillips et al., 2009; Wijntjes et al., 2009). Cross-modal matching has even been demonstrated for plastic molds of real faces, a complex stimulus that may invoke specialized spatial processing mechanisms normally associated with vision (Kilgour et al., 2006; Casey et al., 2007; Dopjans et al., 2009).

Recently, a novel test of cross-modal matching was implemented with three blind subjects who had just recovered sight, a situation that exemplifies the classic test posed by the philosopher Molyneaux (Held et al., 2011). Within 48 hr after surgery, the patients succeeded at intra-modal but not cross-modal matching from touch to vision. However, five days later, without further training, touch-to-vision matching improved significantly. While the implications of these results are not entirely clear, they cast doubt on the naïve assumption that touch provides inputs to an otherwise functional visual channel in the blind. Also disconfirmed is the idea that modality-independent representations formed by blind individuals can be automatically accessed by vision if it becomes available. Such "amodal" representations are discussed in the next section.

On the whole, our review suggests that vision can be translated into touch at a direct spatial level, albeit with considerable reduction in bandwidth. However, this translation does not guarantee a seamless transition to functionality. We next consider a related question, namely, whether visual representations achieve substitution by translation into an amodal level. This form of representation might be spatially isomorphic to the source modality, but amodality could exist without isomorphism.

Functional Equivalence through Amodal Representations

Translation from one sensory channel to another can occur between representations that preserve their modal origins, as long as modality-specific processes allow functionality. An alternative basis for functional equivalence is the convergence of multiple channels onto a common representation. The target representation has variously been called multi-modal, metamodal, amodal, and uni-modal. These terms convey different meanings. Metamodal designates a type of common computation that can be performed on inputs from varying modalities (Pascual-Leone et al., 2001). The term multi-modal implies that the target representation is somehow differentiated or "tagged" by its modal source, but yet functions independently of that tag. This type of structure has also been called supra-modal (Struiksma et al., 2009). Our preferred hypothesis is that the common representation is amodal, which implies that it is abstracted from its modal source. Gallace and Spence (2008) have suggested that an amodal spatial representation is associated with conscious information-processing, in contrast to the unconscious, modality-specific representations that feed into it.

The third term, uni-modal, refers to the possibility that information from multiple sensory channels can be converted to a single, privileged channel. Presumably, when sighted people process spatial information, the privileged channel would be the visual modality. In support of the primacy of visual processing, it has been demonstrated that when sighted individuals are deprived of sight, tactile spatial processing comes to activate cortical regions otherwise associated with visual input. Blind individuals as well show activation in normally visual areas when performing spatial tasks. (See Sathian et al., 2007; 2010, for reviews.) Sathian and Lacey (2007) pointed to the ambiguity of these results, for they may reflect recoding of tactile stimuli into visual images, or it may be that visual regions of the brain process amodal representations.

A growing body of neuroscience evidence suggests that regions traditionally considered to be sensory-specific may normally be involved in multi-modal, if not amodal, processing of specific stimulus dimensions. Two complementary techniques are often used. Brain imaging techniques, such as functional MRI (fMRI) and positron emission tomography (PET), allow identification of the structures that are active in specific tasks, whereas transcranial magnetic stimulation (TMS) produces temporary disruption of these brain regions during the same tasks. The first assesses correlation; the second, causality.

From such studies it appears that some regions at least are organized around commonality of what is computed (shape, motion, face, spatial location, etc.), rather than modality per se (for further discussion, see Pascual-Leone et al., 2005). Various groups studying sensory substitution or developing these devices have pointed to studies showing that what are thought of as primary visual projection areas are activated by auditory and tactile stimulation based on camera input (de Volder et al., 1999; Kupers et al., 2010; for other reviews, see Part 2 of Rieser et al., 2008). Occipital regions of sighted individuals known to be involved with judging visual grating orientation have been shown to be activated during discrimination of tactile grating orientation on the finger (Sathian et al., 1997), and TMS applied to these "visual" regions have led to disruption of the same tactile task (Zangaladze et al. 1999). The lateral occipital complex (LOC), an area known for visual object selectivity, has been shown to be recruited for haptic object perception in sighted individuals (Amedi et al., 2001; 2002), suggesting a general processing region for object geometry.

Further, common processing regions between blind and sighted people have been shown for various stimuli across sensory inputs. Wolbers et al. (2011a) recently reported that sighted and age-matched blind subjects showed activation in the parahippocampal place area (PPA), a region previously shown to be involved with processing of visually-presented scenes, when haptically exploring Lego-block models of rooms. Functional connectivity analyses were specifically directed at the question of whether visual imagery was involved. While co-variation between the PPA and occipital regions was observed for visual processing of scenes by the sighted subjects, it was absent for the haptic condition in either blind or sighted. These results implicate an amodal representation of 3-D scene geometry in the PPA, rather than convergence on a uni-modal one. It has also been found that the Fusiform Face Area (FFA), a region in the fusiform gyrus that responds preferentially when viewing human faces compared to objects or other body parts (Kanwisher et al.,1997), is not exclusive to visual face processing. Category-sensitive activity has been found in the FFA for haptic face recognition in both sighted (Kilgour et al., 2004) and blind participants (Goyal et al., 2006). Finally, another specialized brain region called hMT+ in human cortical region V5, long-known to be recruited for visual motion (Watson et al., 1993) has recently been shown to be involved in auditory motion detection in blindfolded sighted subjects (Poirier et al., 2005) and both auditory and tactile motion in blind participants

(Poirier et al., 2006; Ricciardi et al., 2007; Wolbers et al., 2011b).

A question of practical and theoretical importance remains, however: When an empirical association between a brain area and some information-processing activity is identified, what does this mean in terms of necessity and sufficiency? With respect to necessity, when a brain area conventionally associated with one modality is activated by inputs from another, as is the case when occipital activation accompanies a tactile discrimination task, the role of the activation is unclear. While it could be essential to the task at hand, it might also reflect "downstream" transmission of activation from another area that actually performs the task. Regarding sufficiency, there is no way to guarantee whether the activation observed in the apparently cross-modal area is sufficient for the task. TMS has been used to disrupt processing and so demonstrate causality, but disrupting a single link in a complex chain could be sufficient to impair performance.

Paralleling the studies from neuroscience addressing the question of whether amodal representations exist are a number of behavioral studies, including those described above supporting spatial isomorphism across modalities. Another methodology is predicated on the assumption that switching between modal representations would impose costs on spatial processing, in terms of time or error. The test is then to ask whether spatial judgments that involve multiple locations encoded from different modalities are penalized, relative to their intra-modal counterparts. One study supporting amodality demonstrated that judgments of relative direction could be performed across locations encoded from two different modalities, vision and touch, without significant cost relative to unimodal conditions (Giudice et al., 2009).

We view the evidence for amodal representations as a reason for optimism about at least some forms of sensory substitution. Substitutability is, of course, still limited by the detail and precision in the substituting modality, as determined by modality-specific sensory bandwidth and noise. For example, an amodal representation of spatial layout derived from audition would not be expected to achieve the precision of one derived from vision. However, within the constraints of the haptic system, behaviors that draw on an amodal representation normally encoded from vision could exploit the one encoded from touch without further transformation. This is the premise behind maps for blind people using embossed materials and electronic displays (Ungar et al., 1996; Wall et al., 2006). A person who has lost vision needs no special training to understand the relation between tactual maps and visual maps. However, because close tactual facsimiles of visual maps are too complex to be readily interpretable, tactual maps usually are created with the minimum detail necessary (see Chapter 9).

Synesthesia: Exploiting Natural Correspondences

In this section we consider whether sensory substitution could be "boot-strapped" on natural correspondences between modalities, or synesthesia. More specifically, synesthesia is the spontaneous response of one sensory channel to inputs in another (Harrison et al., 1997; Martino et al., 2001). A channel in this sense may correspond to a sensory modality, as when a musical pitch invokes the impression of a color, or it may refer to intra-modal feature correspondences such as between graphemes and colors, the most common form of synesthesia. The phenomenon has been demonstrated with objective performance measures. For example, while non-synesthetes may have to search for a target grapheme among similar elements in a serial fashion, color/grapheme synesthetes may find that the target "pops out" by triggering a unique color response (Edquist et al., 2006).

The incidence of synesthesia in the general population has been estimated to be about 4% (Simner et al., 2006). Heritability and sex-linked patterns point to a genetic basis for the phenomenon. Bargary and Mitchell (2008) have suggested that it arises from structural anomalies in the brains of synesthetes that lead to deviant cross-activation across cortical areas. Given its rarity and the presumed minimal role for learning, synesthesia cannot be considered a general scheme for sensory substitution. However, more generally prevalent associations across sensory modalities, which Martino and Marks (1999; 2001) call *weak* synesthesia (in comparison to the *strong* form just reviewed), might be useful. For example, Marks (1978) has shown that most people have access to systematic inter-modal pairings, such as associations between color and pitch or temperature.

One particularly intriguing candidate for synesthetically based substitution involving vision is the common association between pitch height (i.e., frequency) and vertical position in the visual field. In an early study, Pratt (1930) reported a directly linear relationship between log frequency and visual height. Walker et al. (2010) found that 3-4 month old infants who were shown a ball moving in time with a changing pitch looked for a longer time when the height of the ball was yoked to a higher pitch than with the reverse mapping. Similarly, pitch height was associated with the sharpness of points on a star.

Should we take this as evidence for innate pitch-height synesthesia? Walker et al. acknowledge that learning was possible even with such young subjects. It should also be noted that the evidence for a cross-modal correspondence in infants does not indicate its directionality. Higher pitch could have been associated with visual items being either higher or lower on the display, and the directionality could vary across subjects without this being picked up by the design. However, the fact that correspondences were exhibited at all in this age range argues at least for a developmental readiness to learn cross-modal correlations.

A cross-cultural study (Eitan et al., 2010) casts some doubt on the potential for strong synesthesia between pitch height and verticality as a basis for sensory substitution. The authors found that while this association is common in Western cultures, it is by no means ubiquitous. Moreover, the specific pitch/vertical mappings varied across subjects, and competing associations to pitch were common. If we assume that the pitch/vertical association is a form of weak synesthesia, these results raise the question of whether in general, naturally acquired associations are consistent enough to be the basis for substitution schemes.

The pitch/vertical association has been used as the basis for devices that substitute hearing for vision (e.g., Auvray et al., 2005; Capelle et al., 1998; Cronly-Dillon et al., 2000; Meijer, 1992)**.** Pitch is used to represent the vertical position of elements in a graph, picture, or each image of a video sequence. Horizontal position is represented by, time, direction (e.g., azimuth from spatial hearing), or a tonal dimension. These devices present an accessible mapping for simple patterns, and the approach has been claimed to be useful for more complex tasks. For example, pitch/vertical mapping has enabled the interpretation of monocular cues to determine depth of a target in the field (Renier et al., 2005). Cortical changes after training on mapping visual height and brightness to sound have been measured as well, both in visual association areas (Renier et al., 2005), and in auditory cortex after extended visual deprivation (Pollok et al., 2005). Subjective impressions of vision have also been reported by users (Ward et al., 2010), which Proulx (2010) termed synthetic synesthesia. However, such reports are difficult to interpret, and methods of validation are lacking.

Rote Learning

In the absence of “boot-strapping” sensory substitution on any of the bases mentioned so far, it remains possible that arbitrary associations between sensory channels could be learned. This idea is encouraged by the theory that with deliberate practice, defined by Ericsson (2004) as "engaging in practice activities with the primary goal of improving some aspect of performance" (p. S3), humans can acquire many types of skills, from complex motor behavior to conceptual mastery such as occurs in chess. A target period of practice for a complex skill is on the order of 10,000 hours.

The mapping of perceptual parameters from one sensory modality to another, even if their computations are based on entirely different input data (e.g., auditory frequencies vs. visual brightness values), can be thought of as just another skill that might be learned. If skills are developed through appropriate practice over extended time-periods, such mappings too may be capable of learning.

It is encouraging in this regard to note that relatively short time periods have led to measurable improvements in sensory substitution. Only 9 hours of training with a spatial array stimulator for the tongue led to a doubling of measured acuity (Sampiao et al., 2001). Geldard (1957) reported a study in which a vibration-to-alphabet scheme ("vibratese") was learned in 12 hours, to a level sufficient for its use in simple text.

The task is daunting, however, when we consider that if sensory substitution is to accommodate the complexity of everyday stimulation, it must involve not just the learning of associations between specific stimuli (e.g., the pitch of a 440 Hz tone = red), but the acquisition of an entirely new sensory "language." No doubt many people could learn to associate a particular visual spectrogram display with the corresponding speech, but as has been discussed, there is limited ability to interpret novel spectrograms representing arbitrary speech segments, even after extensive practice (Zue et al., 1979)**.**

The literature on skill learning indicates that mastery of complex mappings across sensory channels is likely to require extensive practice – if not 10,000 hours, then certainly more than a few. This gives some reason to be cautious about how far rote learning could take sensory substitution, but mappings of at least restricted complexity might be mastered with deliberate, extended practice, particularly if begun early in life. A natural question is whether there is sufficient payoff to motivate the rote learning approach, if that is what substitution is reduced to. If the information gain is not worth the time and effort needed to approach functionality, the system may be ignored.

The proposal that rote learning can be a basis for sensory substitution implicitly assumes that deliberate practice will lead to neural changes that support new capabilities. We next discuss more generally the idea that the plasticity of the brain provides a basis for substitution.

Cortical Plasticity

There is little doubt that the brain's highly adaptive nature helps explain why sensory substitution is possible to at least a limited extent. In connection with his seminal work with the Tactile Vision Substitution System, which used a video camera to drive an electrotactile display, Bach-y-Rita (1967; 1972) speculated that the functional substitution of vision by touch resulted from cortical plasticity that allowed incoming somatosensory input to be analyzed by visual areas. Though the idea was radical for its time, cross-modal brain plasticity has been confirmed by many subsequent studies.

The brain is a highly malleable organ, and there are multiple types of plasticity that arise from its ability to change in response to sensory input. For instance, so-called use-dependent expansion refers to plastic change resulting from prolonged focal stimulation of a peripheral organ. The reading fingers of expert blind Braille readers show expanded cortical representation in somatosensory cortex (Pascual-Leone et al., 1993; Sterr et al., 1998), as do the finger representations for expert string players (Elbert et al., 1995).

Much of the cross-modal plasticity research has focused on long-term brain reorganization as a result of early-onset blindness. Research in this area has shown that the visual cortex of skilled blind Braille readers is activated when they are reading Braille (Büchel, 1998; Sadato et al., 1996), and TMS delivered to these same occipital regions interferes with the perception of Braille in similar subjects (Cohen et al., 1997). Brain imaging of an adult with the rare ability to read print visually with low acuity, and also read Braille by touch, revealed complementary organization of early visual areas. Regions normally activated by the fovea were dedicated to touch, while those normally receiving projections from the periphery were activated by vision (Cheung et al., 2009). Although auditory plasticity is not our focus here, similar recruitment and disruption of occipital regions by various auditory stimuli has also been demonstrated in blind people (Kujala et al., 2005; Merabet et al., 2009; Weeks et al., 2000).

It may be tempting from such findings to conclude that plastic change is only possible with early onset blindness and that those who lose their vision later in life will not benefit from the increased computational resources associated with neural reorganization. While it is true that plasticity tends to be greatest before adolescence (Rauschecker, 1995), a growing body of evidence has shown that this so-called critical period is neither necessary nor limited to early life. For instance, late-onset blind individuals show many of the same cross-modal involvement of occipital regions as their early blind peers for purely spatial tasks (Goldreich et al., 2003; Stilla et al., 2008), suggesting that the differences often observed with occipital activation from Braille reading by early blind individuals may be practice-related or due to non-spatial linguistic factors (Sathian et al., 2007). These studies suggest that the brain is able to flexibly adapt to changes in afferent input across the life span. For reviews of cross-modal plasticity in the blind, see (Merabet et al., 2010; Sathian et al., 2007; 2010).

Remarkably, plastic change is not restricted to permanent changes in afferent inputs, as experiments with sighted people who have been blindfolded for only temporary periods have shown demonstrable effects. Behavioral changes leading to increased discrimination of tactile grating orientation have been shown to occur within 1.5 hours of blindfolding (Facchini et al., 2003), and people blindfolded for five days showed improved Braille discrimination performance compared to sighted controls who underwent the same training (Kauffman et al., 2002). Neuroimaging results with sighted participants after 5 days of blindfolding showed that tactile stimulation activated the occipital cortex and application of TMS disrupted tactile perception and Braille discrimination in a similar manner as has been shown in the blind (Merabet et al., 2008). Interestingly, this same study showed that the dramatic plastic changes observed with 5 days of blindfolding were completely reversed within 24 hours of removing the blindfolds. Although the mechanisms supporting this short-term plasticity may differ from long-term blindness, e.g., unmasking of inhibitory connections vs. forging of enduring cortico-cortical connections (Pascual-Leone et al., 2001), such findings suggest that the importance of the brain's potential for change should not be underestimated.

Image Preprocessing and Artificial Intelligence

In reflecting on mobility experiments with the Tactile Vision Substitution System, one of its developers, Carter Collins, made the following comments: “However, on testing this system outdoors in the real world sidewalk environment, it was found that there was simply too much information which overloaded the tactile system. Perhaps 90% was the wrong kind of information, that is, comprised of interfering tactile detail in the background surrounding the objects of regard, which appeared to mask the primary mobility information. The bandwidth of the skin as an information-carrying medium is limited and apparently cannot handle the vast amount of data in a raw television image as complex as a sidewalk scene." (Collins, 1985, p. 37). He went on to suggest: "For the ideal mobility system of the future, I strongly believe that we should take a more sophisticated approach, utilizing the power of artificial intelligence for processing large amounts of detailed visual information in order to substitute for the missing functions of the eye and much of the visual pre--processing performed by the brain. We should off-load the blind travelers' brain of these otherwise slow and arduous tasks which are normally performed effortlessly by the sighted visual system. ... We should extract features in the scene which are essential for mobility." (Collins, 1985, p. 41). His prescient remarks point to the vital importance of not delivering information to touch and hearing that exceeds their processing capacities, as discussed earlier. Rather, one can use either simple image preprocessing or the more powerful techniques from artificial intelligence to provide information, including linguistic information, that is more suited to the processing capacities of touch and hearing. Consider, for example, the challenge of scene perception. Video data from a video camera augmented with laser range finding could be used to select the information within a narrow depth of field in front of the user and display only the information that is important for obstacle avoidance. The work of Gonzalez-Mora et al. (2006) illustrates the use of such preprocessing in connection with an auditory vision substitution system.

Going beyond simple signal processing are artificial intelligence techniques for extracting more abstract information such as object identity, features of the environment, and impending collision targets, information that can then be presented to the user by way of perceptual displays and language (Collins, 1985; Katz et al., 2010). A nice example is the Blind Driver Project by Dennis Hong and his collaborators at Virginia Tech University in response to an initiative of the National Federation of the Blind Jernigan Institute. The group has instrumented a car with video cameras, laser range finders, GPS, and other sensors and a variety of non-visual interfacts that include auditory commands and a haptic display of airjet stimulators that the driver can feel with the hand. Blind people are able to use the display to steer a closed course and to avoid large obstacles scattered in front of the vehicle[1] An important factor in the success of the project is the result of using artificial intelligence techniques to compute the edges of the road and obstacles and to present only that information on the haptic display. Removing all of the clutter that would normally appear with delivery of the raw video stream has the same benefit as starting with only high contrast features of the environment (Panel D of Figure 8.2). It remains to be seen whether the project will have success with demands of unconstrained real city driving.

Implications of Processing Differences between Blind and Sighted people

Given that blindness is the most common target for sensory substitution, and the indications that the lack of sight profoundly changes brain function, it is important to consider whether models of spatial information processing derived from studies of sighted individuals also apply to the blind. A related question is whether the differences in sensory experience and deliberate practice of sighted and blind affect their processing. In particular, sighted or late-blind subjects are more likely to be able to use visual mediation. For example, visual experience in interpreting 3-D cues might explain why late-blind outperform early-blind in some studies of the ability to recognize tactually presented pictures (Heller, 1989).

Röder and colleagues have suggested that early blindness alters inter-sensory processing by reducing integration across modalities. Sighted individuals showed a greater tendency to

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[1] http://www.romela.org/main/Blind_Driver_Challenge

integrate tactile and auditory taps when judging numerosity (Höttig et al., 2004a). Blind people also showed a greater ability to filter out stimuli from a task-irrelevant modality while attending to their spatial location, as measured by event-related potentials (Höttig et al., 2004b). Studies of a group who had congenital binocular cataracts early in life indicated that their audio-visual interactions, once sight was restored, were reduced relative to controls (Putzar et al., 2007). Neural and/or processing differences between sighted and blind have important implications for the effectiveness of sensory substitution, as studies with sighted or late-blind people might not be sufficiently capable of generalization to indicate substitutability for the congenitally blind. This point is made by a study comparing blind and sighted with respect to brain areas activated during navigation aided by a tongue stimulator (Kupers et al., 2010). Consistent with the idea that blindness induces brain re-organization, the blind produced activation more like the sighted when walking under visual guidance. With the same device, congenitally blind out-performed sighted controls on obstacle detection and avoidance (Chebat et al., 2011).

Recommendations for the Design Process

A theme throughout this chapter is that while there is significant potential for sensory substitution, basic research has also pointed to clear limitations. Unfortunately, the motivation for design of sensory substitution devices, and assistive technology more generally, has often been ad hoc rather than based on sound theory or empirical findings, and evaluations tend to be limited to controlled settings. The failure to recognize the processing constraints of perception and cognition has resulted in limited utility of sensory substitution devices for supporting real-world behaviors. In addition, naïve assumptions about the end-users, rather than systematic studies with first-person reports, have ultimately reduced the enthusiasm for these devices and their adoption by the target demographic. In this final section, we highlight some key considerations in the design of assistive technology that we hope will capitalize on the basic promise and avoid some of the pitfalls demonstrated in the past.

Understanding the Information Flow from Function to Display

As we have emphasized throughout this chapter, simply having a technological solution for converting visual input into tactile or auditory output is not sufficient for successful sensory substitution. Effective devices must consider the capabilities and limitations of the human perceptual-cognitive system that underlie the function to be supported.

We postulated that a principled approach to using touch or hearing as a substitute for vision has two essential steps: (1) Identify the information that is most effective in enabling the desired function, and (2) determine how best to display this information to the substituted modality. Note that more information is not necessarily better; what is needed is to provide information that is directly relevant to the task at hand. Consider the insights about the information overload delivered via the Tactile Vision Substitution System, which were lessons learned only at the late stage of real-world testing (Collins, 1985).

Any serious effort to develop sensory substitution devices and assistive technologies must be theoretically motivated and scientifically sound. We believe that principled design, based on initial due diligence with regard to the scientific base, will aid in avoiding some of the common errors that have limited the use of sensory substitution devices. Developers of new devices should also be prepared to conduct empirical research at multiple points during the design process, including not only iterative usability testing but also basic psychophysical experiments to understand underlying processes. Practically speaking, what this means is that a group that takes on the task of creating a useful sensory-based aid will have to include expertise in related theory and methods as well as technology.

Considering the End User from the Starting Point Onward

The starting point for many assistive technologies appears to be the laudable aim of providing a solution to a practical problem. Too often, unfortunately, the problem is envisaged by the developer, and the solution is directed by the availability of engineering and technical tools. The result is the "engineering trap": A product is developed that may be interesting and even elegant, and aims to solve a real problem, but in actuality has little functional utility or even relevance for the everyday challenges of its intended users.

Given that technology exists that may be directed at an assistive problem, avoiding the engineering trap requires adhering to several practices at the starting point of a project: (1) Identify the user population who are envisioned to have the problem; (2) Assess the user needs, that is, the elements of the solution that the target population believes are necessary; (3) Determine whether the intended implementation will be functional not only technically, but in the context of human information-processing capabilities and practical constraints. The first practice is obvious for development of visual sensory substitution devices, which are almost always designed for blind / low-vision individuals. The third practice is considered a necessary step in engineering and design, although it is generally not taken far enough. It is the second step that is often overlooked entirely, and with consequences: insufficient characterization of user needs results in devices which are not accepted and have little functional utility.

Two relatively easy and inexpensive means of consulting blind individuals are survey instruments and focus groups. Surveys are easy to administer and score, but they are neither interactive nor scenario driven. The results from focus groups may be harder to quantify, but the clear advantage is that they provide invaluable feedback from interactive exchange and hands-on experience with prototypes. A combined approach, including iterative input from users as the project progresses, is most informative.

User input at the starting point is needed for two critical aspects of an intended assistive technology. One is the generality or specificity of the functions the technology is intended to serve. Clearly we favor special-purpose devices that support a specific function in everyday life such as navigation, rather than general-purpose devices. A second critical aspect of technology is the learning period required in order for it to be effective. Although an intuitive system is always preferable, users are likely more amenable to a steeper learning curve when the device is providing a solution to a real-world problem that is not addressed by other technologies and that has an impact on independence, quality of life, education, and/or vocation (Giudice et al., 2008). Developers beware: Only first-person accounts can provide an assessment of the learning/usefulness trade-off.

End-users should be consulted not only about a device's functionality, but its aesthetic appeal. Developers unfortunately often neglect this aspect of design, operating instead on the naïve assumption that access to information is more important than aesthetic considerations. To the contrary, in a study of user preferences about body-worn assistive technologies, cosmetic acceptability was often rated as more important than the potential benefit afforded by the device (Golledge et al., 2003). Where the goal is to create technology that is minimally intrusive, the reality is that sensory substitution devices that require visible hardware such as cameras, headphones, or electrotactile stimulators are not invisible. Both form and function must be considered; aesthetic impact cannot be ignored.

Concluding Remarks

In sum, the role of a sensory-substitution device is to support the demands and interests of the user and to enhance capacities that are otherwise difficult or not possible from non-visual means. A sensory substitution device should emphasize task-specific information, carefully consider the end-user's information needs and requirements, support individualized selection of desired information and perhaps most important, should not take over functions or provide information that the user is capable of completing and receiving without the device's assistance (Jacobson et al., 2011). Learning from past blunders and following the suggestions in this chapter will provide a good starting point for designers to develop future sensory substitution devices based on theoretically-motivated, user-inspired design.

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