CHAPTER 15

Perception and Interactive Technology

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"What does it mean, to see?" was the question that David Marr used to motivate his computational approach to understanding *Vision* (Marr, 1982). Marr's answer, building on Aristotle, was that "vision is the process of discovering from images what is present in the world, and where it is" (page 3). Although we humans might have a preference for visual perception, we are endowed with other senses that provide us with a rich experience (Chapters 2, 3, 4, 5, and 14, this volume). Therefore, the broader question might be: What does it mean, to perceive? Although this might be seen as a philosophical question of sorts, it gets to the important issue of how we define perceptual experience scientifically so that we may study it. The importance of defining it is crucial for research applications: If we aim to restore a sense such as vision in blindness or hearing in deafness, what does it mean to see or to hear such that we will know when restoration has been successful? This chapter reviews the interaction between multisensory perception and interactive technological approaches to sensory rehabilitation. It builds on research in multisensory perception, sensory impairment, and the development of cognition to provide a foundation for understanding the psychological and neural basis for sensory rehabilitation. The interface between experimental psychology and technology provides challenges for basic and applied research, and, as a result, great opportunities to explore psychology and cognitive neuroscience in novel ways.

We will first provide an outline of human sensory perception using single (unisensory) and multiple (multisensory) senses. This first section highlights the interplay between different sensory modalities for the construction of a precise and accurate representation of the environment and the mechanisms our brains have developed to deal with physical uncertainty. Thereby, we specifically focus on optimal multisensory integration and its development during ontogeny. We then look into the adaptation of human perception to sensory or motor deficits—that is, when one or multiple senses are impaired, or the motor system isn't functioning normally. We describe how sensory loss/impairment impacts individuals in their everyday life and how deficits in one sense affect development in the remaining, intact senses. Also, the role that action and motor impairment plays in the perceptual framework is discussed. We then outline current sensory rehabilitation techniques, with focus on auditory and visual rehabilitation, as these domains are more extensively investigated, thereby drawing a clear distinction between sensory restoration and sensory substitution. Their function and

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benefits of these different techniques for certain populations will be discussed, and the chapter closes with some remarks on the outlook of interactive technology in sensory rehabilitation research and application.

UNISENSORY AND MULTISENSORY PERCEPTION

Our sensory systems have been shaped by evolutionary processes in such a way that we are well-adapted to the natural world we live in and respond accurately to biologically relevant events (Kaas, 1989; Machens, Gollisch, Kolesnikova, & Herz, 2005; Nummela et al., 2013). Humans have a number of senses that consist of arrays of different types of receptors: electromagnetic receptors, mechanoreceptors, chemoreceptors, thermoreceptors and pain receptors. We take up information from the environment using these receptors by transforming the different forms of energy (e.g., electromagnetic radiation, pressure waves) into electrical signals. This process is called transduction and enables us to perceive the different forms of energy in one and the same entity—namely, in electrical impulses. These impulses, in turn, get sent to the central nervous system via neural pathways. Our central nervous system then processes and combines the information in a way that makes us perceive and recognize the world around us, eventually leading to ecologically relevant behavior. The process of perception is strongly characterized by the combination of different, as well as redundant information, derived from our sensory organs. It is not a unidirectional process but stays in constant dynamic interaction with the actions we make. We actively use our body to facilitate perception by sampling our environment in the best way possible. For example, we need to actively explore or manipulate an object in order to gain enough information to recognize it (Chapter 5, this volume; Hollins & Risner, 2000). This clearly makes touch an inherently active sense. However, with the aim of controlling our actions appropriately, perception must be frequently updated via sensory feedback, which arises from our actions. In fact, not only touch but also other senses like vision, proprioception, and audition critically depend on the fine-tuned recalibration of action and perception (Cressman & Henriques, 2011; Proulx, et al., 2015).

The environment we live in is not stable but complex and dynamic. Moreover, all stimuli in our environment can be differentiated in multiple features. For example, sounds vary in amplitude and pitch while light varies in hue, luminance, and color. This vast variation of environmental stimuli that, on the one hand, supports our brain in structuring our complex lives, also emphasizes the necessity of our sensory systems to be quite flexible in the way they process incoming information, regardless of whether they arise from the same or from different modalities (Chapter 14, this volume).

Here is an example: in order to judge visually the spatial distance of an object our eyes provide us with a number of different visual cues. The perception of depth, which is crucial for estimating the distance and relative position of objects in space, arises from the combination of information from monocular cues like perspective, occlusion, shading, or relative size as well as binocular cues like retinal disparity and convergence. Furthermore, extra-retinal cues like signals from the eye muscles have also to be taken into account by the brain to determine in which direction the eyes are looking. This already shows that vision is much more complex than we often think and that even within one sensory system the amount of information our brain processes in order to compute a single object feature—like depth—is immense and not restricted to the visual sense alone.

When we stick to the example of depth as a distance cue, we find that vision is the sense that is dominantly used for estimating spatial depth at distances that are out of physical reach (Battaglia, Jacobs, & Aslin, 2003). However, our sense of hearing can additionally extract spatial distance cues from our environment using frequency spectrum, inter-aural loudness difference and inter-aural time difference (Moore, 2003). This gets particularly important when information in the environment is limited or ambiguous. Vision itself, for instance, is often ambiguous due to projection of a three-dimensional visual scene onto a two-dimensional retinal image. Mapping the two-dimensional image back into a three-dimensional scene can result in many different possible outcomes. Similarly, reliance on self-motion can result in well-known perceptual misinterpretations, as the somatogravic illusion shows (see Figure 15.1). Here, the vestibular system, which provides us with rotational and translational movement cues, is tricked in a way that acceleration or deceleration of, for example, an airplane evokes the sensation of the own body facing upwards or downwards, which is in turn misperceived as an upward or downward tilting of the airplane. This interpretation can result in dangerous maneuvers if not corrected for by vision. Therefore, experience and use of additional sensory information are crucial. This shows that, if ambiguous stimuli were processed by only one modality, the information they convey would remain ambiguous and perception would be less reliable. Also, in other circumstances in which one sensory modality is unavailable, other senses can compensate for this lack of information. For example, when navigating in complete darkness, touch, hearing or self-motion/interoception can compensate for lacking visual information (Petrini, Caradonna, Foster, Burgess and Nardini, 2016; Tcheang, Bülthoff, & Burgess, 2011).

Besides situations in which the information from one sense is ambiguous or missing, there are situations in which the presence of environmental or internal noise can drastically affect our perception. Noise is present in all the stimuli surrounding us and arises from their physical nature, like clutter affecting sound waves or quantum fluctuations of light. Also, internal noise, which results from a variability in neural coding or the fluctuation of attention, can affect perception at many different stages of processing. For example, one may think that trying to walk straight lines while being blindfolded is an easy task. As long as the distance to be traveled is only a couple of meters, then probably it is. However, Souman and colleagues (2009) showed that during navigation it is much harder to maintain a straight walking route when the information input is limited to fewer senses, the level of sensory noise is increased in the absence of visual calibration. In one experiment in which participants were asked to walk a straight line, even participants who were not blindfolded could not walk straight on cloudy days. When the sun was not visible, they started to walk in circles, whereas the other participants who walked on sunny days followed almost perfectly straight routes. Souman and colleagues concluded that when the vestibular system integrates information on rotation rate with no input from other senses (like vision), it accumulates noise. As a result their participants' estimated walking direction tended to get biased to one side resulting in circular rather than straight routes, similarly to those who were blindfolded (Souman, Frissen, Sreenivasa, & Ernst, 2009).

Multisensory Integration

Now, how does the brain deal with missing, noisy, or ambiguous information from

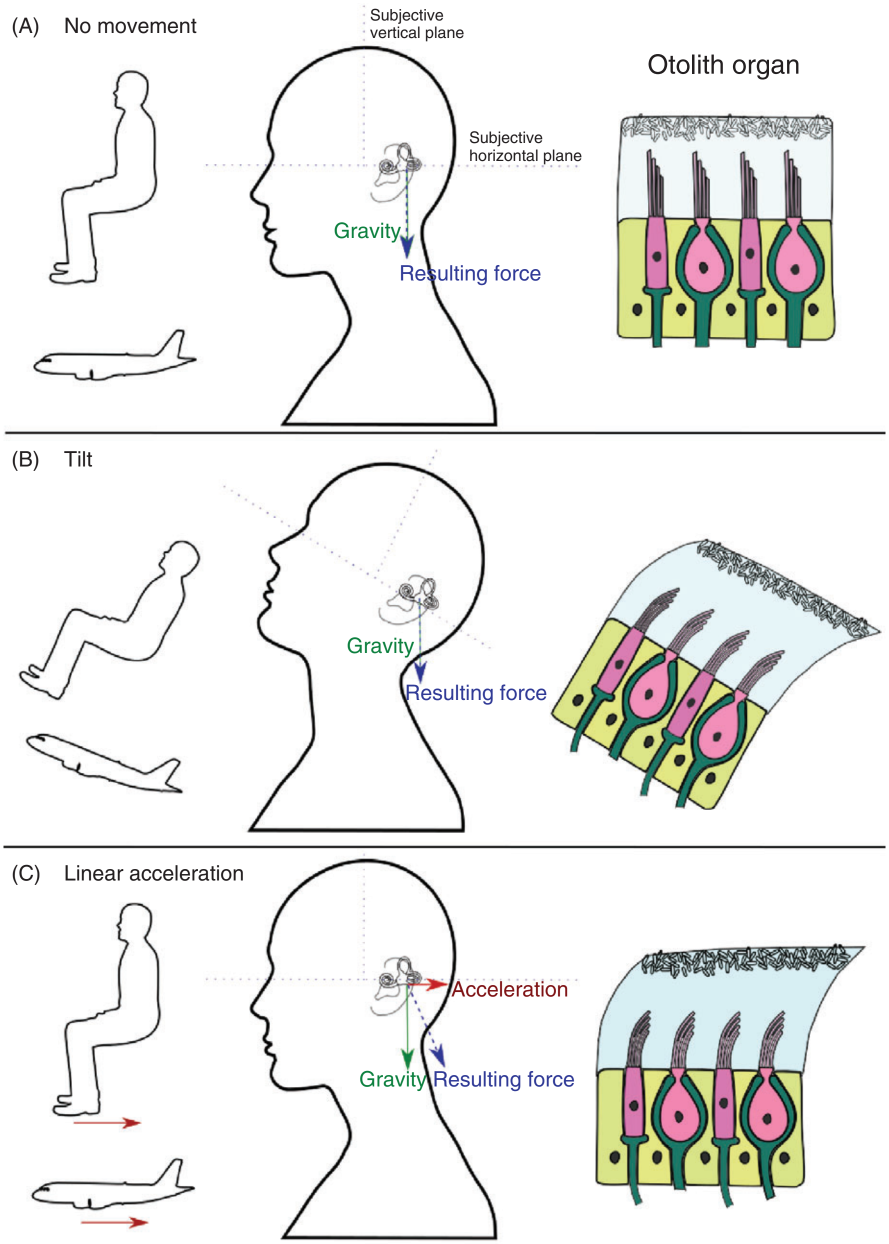

Figure 15.1 The somatographic illusion, which is frequently encountered in aviation, is an illusion by which the brain confuses high acceleration or deceleration with forward or backward tilting. It results from the ambiguous information arising from a displacement of the otolithic membrane above the excitable hair cells in the otolithic organs of the vestibular system (right column). In situations in which the body is not accelerating nor deccelerating (A) gravity is the only force acting on the state of the hair cells and can be used to interpret the position of the head relative to the ground. (C) During fast changes of movement, on the other hand, acceleration forces lead to a displacement of the otolithic membrane and result in a bending of the hair cells, similar to the bending of the cells during tilt (B). As the brain uses information from the bending of hair cells to compute the head's position in space and relative to the ground, head tilt and translational movement can both lead to the same perceptual interpretation. Translational acceleration shifts the membrane in the same direction as an upward head tilt, whereas translational deceleration results in a similar response to a downward tilt. Visual information helps disambiguating this perceptual illusion.

the environment and still comes up with an adequate solution? It achieves this by combining redundant information synergistically to reduce uncertainty and overcome sensory ambiguity resulting from noise or the lack of sensory information (Chapter 14, this volume; Ernst & Banks, 2002). For example, when we estimate an object's shape we can make judgments based on visual as well as haptic cues. When experienced simultaneously, the brain integrates the shape information across the two senses in order to provide us with the most reliable sensory estimate (Helbig & Ernst, 2007). Statistically optimal multisensory integration describes the process by which we combine information from different sensory inputs and dynamically weight them, depending on their reliability, in order to achieve a more robust percept (Ernst & Banks, 2002; Ernst & Bülthoff, 2004; Knill, 2007; see Figure 15.2). The resulting accuracy and precision of our multisensory percept exceeds that granted by unisensory information alone. This weighting process either biases our percept toward the most reliable sensory cue for a particular task (often resulting in one sense dominating the others, for example, vision dominating sound in spatial tasks) or, in case of a similar level of reliability among different senses, determines optimal integration by calculating a weighted linear average of these sensory estimates. What is more is that during integration, uncertainty within both the perceptual system as well as the motor system are taken into account to help planning and predicting optimal behavior (Knill & Pouget, 2004; Todorov & Jordan, 2002).

The maximum likelihood estimation (MLE) model underlying statistically optimal multisensory integration has often been used to successfully predict different behavioral outcomes in perceptual tasks like visuo-haptic and audio-haptic size estimation (Helbig & Ernst, 2007; Petrini, Remark, Smith, & Nardini, 2014), audio-visual position judgments (Alais & Burr, 2004), visual-tactile event counting (Bresciani & Ernst, 2007), size and orientation discrimination (Gori, Del Viva, Sandini, & Burr, 2008) as well as the use of vision and self-motion/interoception for navigation (Nardini, Jones, Bedford, & Braddick, 2008; Petrini et al., 2016; Tcheang, et al., 2011; Zhao & Warren, 2015). In addition, the same model seems to well explain the underlying multisensory neural mechanisms.

A great amount of our knowledge on the neural processes underlying multisensory integration can be attributed to the emergence of technologies like electroencephalography, functional brain imaging, or transcranial magnetic stimulation (e.g., Beauchamp, Pasalar, & Ro, 2010; Dekker et al., 2015; Foxe et al., 2002; Giard & Peronnet, 1999; Helbig et al., 2012; Merabet et al., 2008). However, the first evidence for neural multisensory processes comes from Stein and Meredith's studies on single neurons (Meredith & Stein, 1983; Stein & Meredith, 1993). They recorded electrical signals of neurons in the superior colliculus (SC) of cats in response to auditory, visual, and audio-visual stimuli. Neurons in this region, but also other regions, responded to all stimuli types, but showed different response strengths toward unimodal (auditory, visual) and multimodal (audio-visual) stimuli, with multimodal stimuli evoking greater responses than unimodal ones (see Figure 15.3). Most strikingly, these enhanced responses were even greater than the sum of the responses toward unimodal stimuli ("super-additivity"). Besides an increase in response strength, multisensory integration has also been characterized by shortened response latencies, meaning that single neurons respond faster to multisensory than unisensory stimuli (Rowland & Stein, 2007).

There is also increasing evidence that multisensory processing even takes place in what are normally considered primary sensory areas, leading some to theorize that the

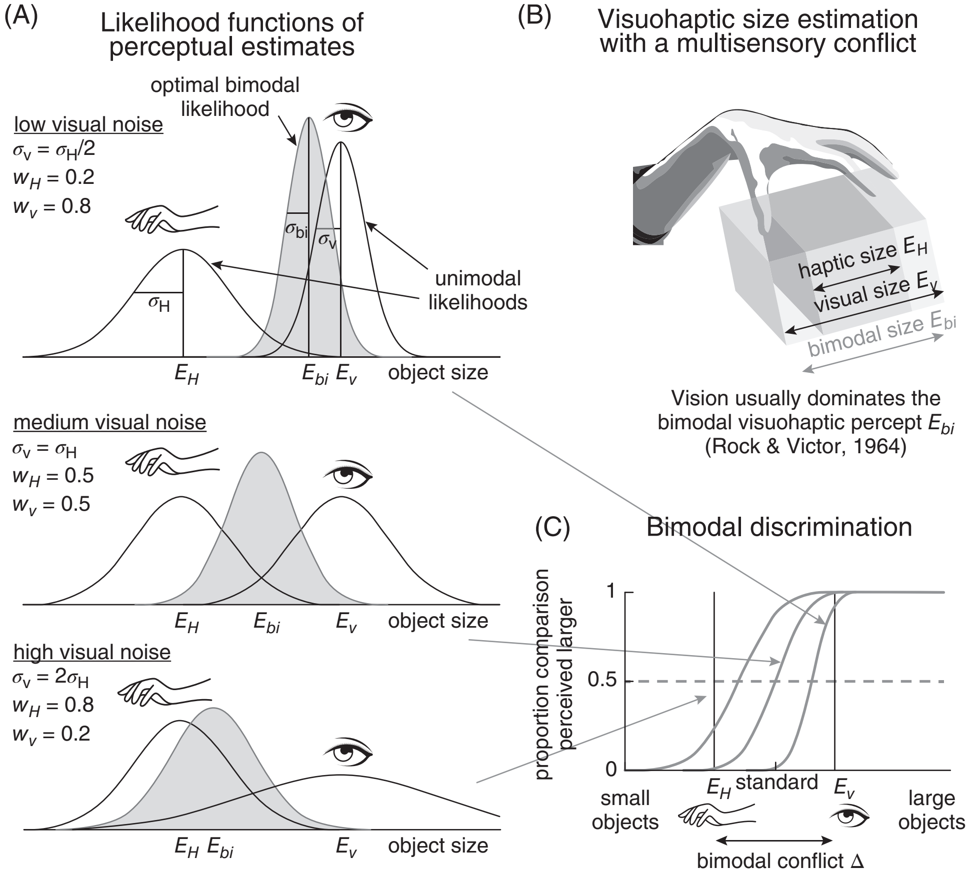

Figure 15.2 Model showing statistically optimal integration of visual and haptic cues in an object size estimation task. (A) Probability functions indicating the likelihood of the object being perceived as having a certain size. Bimodal likelihood function (gray) is the weighted product of the two unimodal likelihood functions, and depends on the uncertainties in the visual (σ_V) and the haptic (σ_H) functions. E_{bi} indicates the combined perceptual estimate of visual (E_V) and haptic (E_H) unimodal size estimates. An increase in visual noise leads to a stronger weighting of the haptic likelihood function, thereby pulling the bimodal size estimate closer to the haptic one. (B) Illustration of visuo-haptic size estimation task, whereby participants judge the size of an object using vision and touch. Introducing a conflict between visual and haptic size helps determining the weights placed on the unisensory estimates during combination. (C) Psychometric functions indicating the relationship between actual stimulus size and the proportion of comparison stimuli being perceived as larger than a standard stimulus. Visual (E_V) and haptic (E_H) cues of the standard stimulus give discrepant information (Δ). The discrimination performance indicated by the functions can be experimentally measured and informs us about the bias and precision of the bimodal estimate (as indicated in panel A).

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brain is organized in a "metamodal" (Kim & Zatorre, 2010; Pascual-Leone & Hamilton, 2001; Proulx, Brown, Pasqualotto, & Meijer, 2014), or "supramodal" (Matteau, Kupers, Ricciardi, Pietrini, & Ptito, 2010; Ricciardi, Bonino, Pellegrini, & Pietrini, 2014; Struiksma, Noordzij, Neggers, Bosker, & Postma, 2011), fashion. That is, rather than

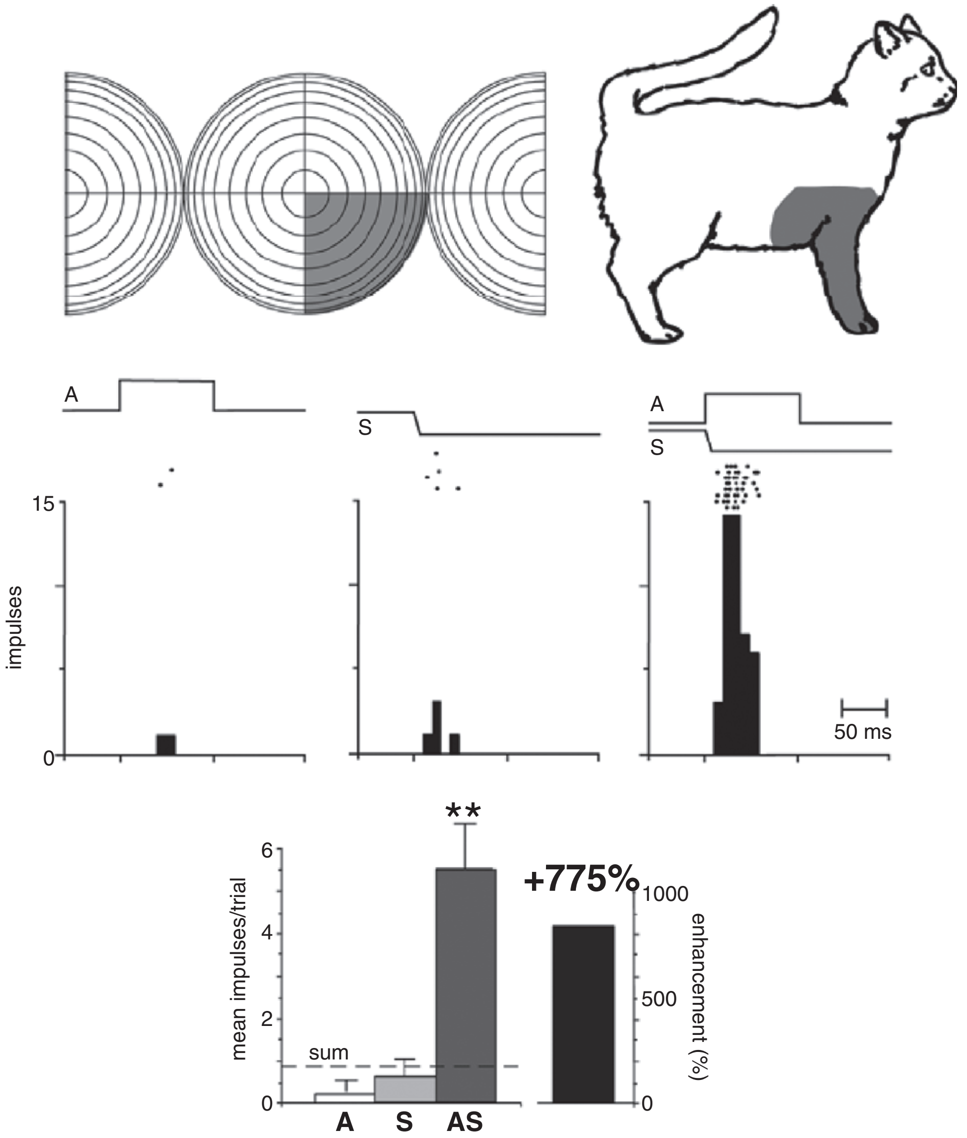
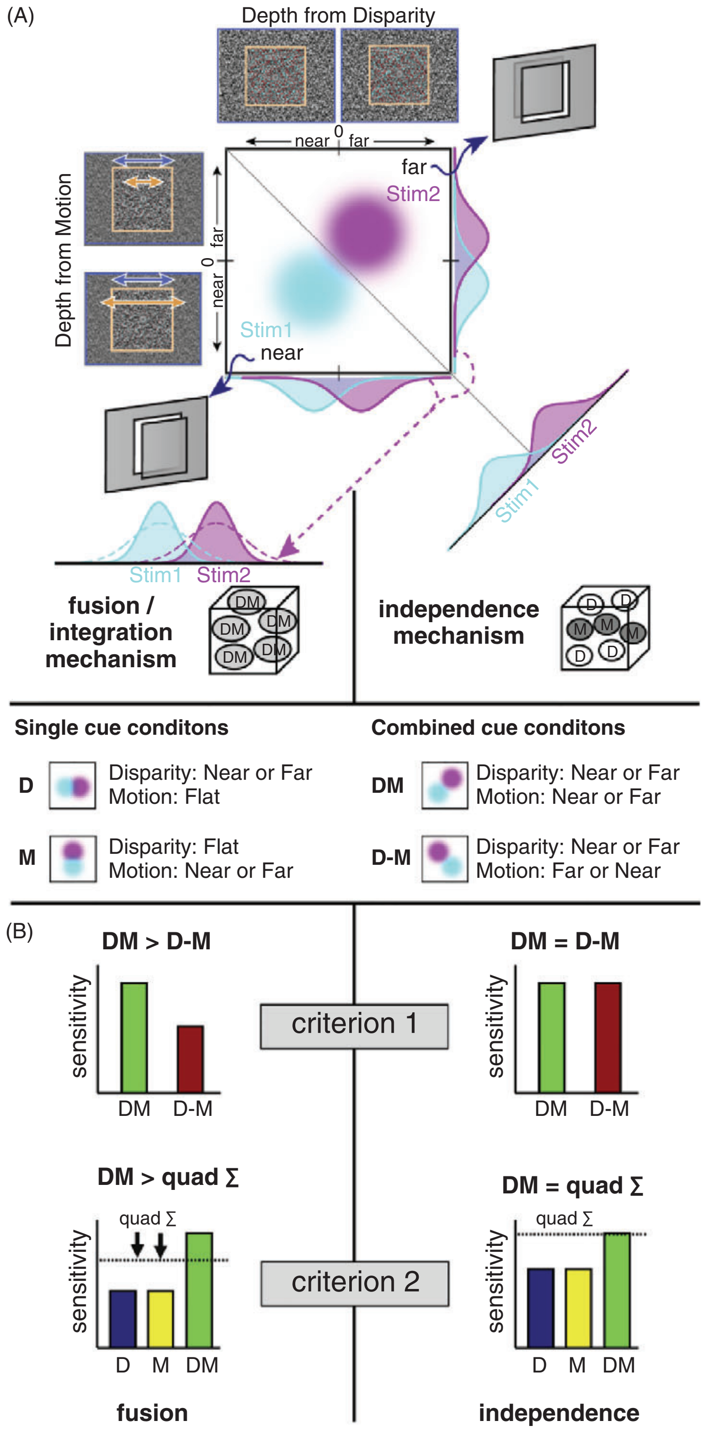


Figure 15.3 Example of super-additive responses during integration of auditory and somatosensory information in a neuron of the cat anterior ectosylvian sulcus (AES). The top panel indicates the spatial overlap between the cat's auditory and somatosensory receptive fields used for stimulus presentation (shaded regions). Presentation of auditory (A) or somatosensory (S) stimuli alone elicited only few neural responses, as can be seen in the raster plots and histograms. Simultaneous and spatially coinciding presentation of auditory and somatosensory stimuli evoked a significantly stronger response. The bar graph at the bottom shows a summary of neural responses to both unimodal (A, S) and simultaneous bimodal (AS) stimulation. This neuron exhibits a larger response enhancement to the bimodal stimuli presentation compared to the sum of the two unimodal ones (**$p < 0.01$).
Source: From Wallace (2004). Reprinted with permission.


(A)
Depth from Disparity
near
0
far
Depth from Motion
far
0
near
far
Stim2
Stim1
near
Stim1
Stim2
Stim1
Stim2
fusion / integration mechanism
DM
independence mechanism
D
M
Single cue conditons
D
Disparity: Near or Far
Motion: Flat
M
Disparity: Flat
Motion: Near or Far
Combined cue conditons
DM
Disparity: Near or Far
Motion: Near or Far
D-M
Disparity: Near or Far
Motion: Far or Near
(B)
DM > D-M
sensitivity
DM
D-M
criterion 1
DM = D-M
sensitivity
DM
D-M
DM > quad Σ
quad Σ
sensitivity
D
M
DM
criterion 2
DM = quad Σ
quad Σ
sensitivity
D
M
DM
fusion
independence

having a sensory-based organization, the brain instead has a computationally defined functional architecture that is task-based (Pascual-Leone & Hamilton, 2001). It therefore might be best to try and consider the brain from a multisensory rather than unisensory perspective (Ghazanfar & Schroeder, 2006).

Development of Multisensory Integration

The ability to use redundant sensory cues to enhance perception seems to be present very early in life. For example, infants and young children find synchronous redundant stimuli across visual and auditory modalities very salient (e.g., Bahrick & Lickliter, 2000, 2004; Bremner et al., 2011; Lewkowicz, 1996, 2000; Morrongiello, Fenwick, & Chance, 1998). That is, human infants during the first year of life (Lewkowicz, 2010) have been shown to process audio-visual information on the basis of temporal synchrony rather than sensory reliability. The reliance on temporal and spatial correspondence between cues is a stronger binding factor until late childhood. Indeed, the ability to filter out irrelevant information across modalities when cues are in temporal synchrony starts rather late (not before 11 years of age; Petrini, Jones, Smith, Nardini, 2008). Similarly, speech pattern recognition and speech perception become more accurate around that age range (Eisenberg, Shannon, Martinez, Wygonski, & Boothroyd, 2000; Petrini & Tagliapietra, 2008). Barutchu et al. (2010) hypothesized that attention and other higher order cognitive processes regulate cross-modal integration and that the maturation of these processes delays the development of multisensory integration (Barutchu et al., 2010). However, it's not been until recently, that fMRI studies have shown that cue integration properties in the visual cortex only develop around the same age (Dekker et al., 2015, see Figures 15.4a and 15.4b). Until then,

Figure 15.4a Detection mechanisms and integration criteria of visual cue integration during depth perception. (A) Participants were presented with dot displays that used binocular disparity (differences in dot positions between the two eyes) and relative motion (movement speed of target dots relative to surrounding dots) to simulate depth of a target square that was either in front or behind its surround. Depth estimators for both stimuli are displayed as bivariate Gaussian distributions (as indicated by the blue and pink blobs in the motion-disparity space). In the area where the conflict is largest, fusion of both stimuli (left panel) would result in a combination of the cues and reduce variance—that is, the two cues would be integrated. A mechanism that would treat the sensory information independently (right panel) would result in a greater separation of the stimuli. Using these two cues, participants were tested on two single cue and two combined cue conditions: D: disparity was altered while relative motion was kept constant; M: relative motion was altered while disparity was kept flat; DM: both cues conveying congruent information (e.g., both cues suggested the target square was near); D-M: both cues conveying incongruent information (e.g., disparity suggested that the target was far while motion suggested it was near). (B) Following the two different mechanisms explained before (fusion or independence), two predictions can be made for each scenario: Criterion 1: the sensory fusion mechanism (left panel) would predict that sensitivity is enhanced when both sensory cues provide congruent information, compared to incongruent information. Following the independence mechanism, bimodal sensitivity would not be affected by congruency. Criterion 2: fusion of sensory information would predict sensitivity to be greater than the quadratic sum of single cue sensitivity when both cues provide congruent information. On the contrary, the independence mechanism predicts that sensitivity of DM is equal to the ideal observer prediction (quadratic sum).
SOURCE: From Dekker et al. (2015). Reprinted with permission.

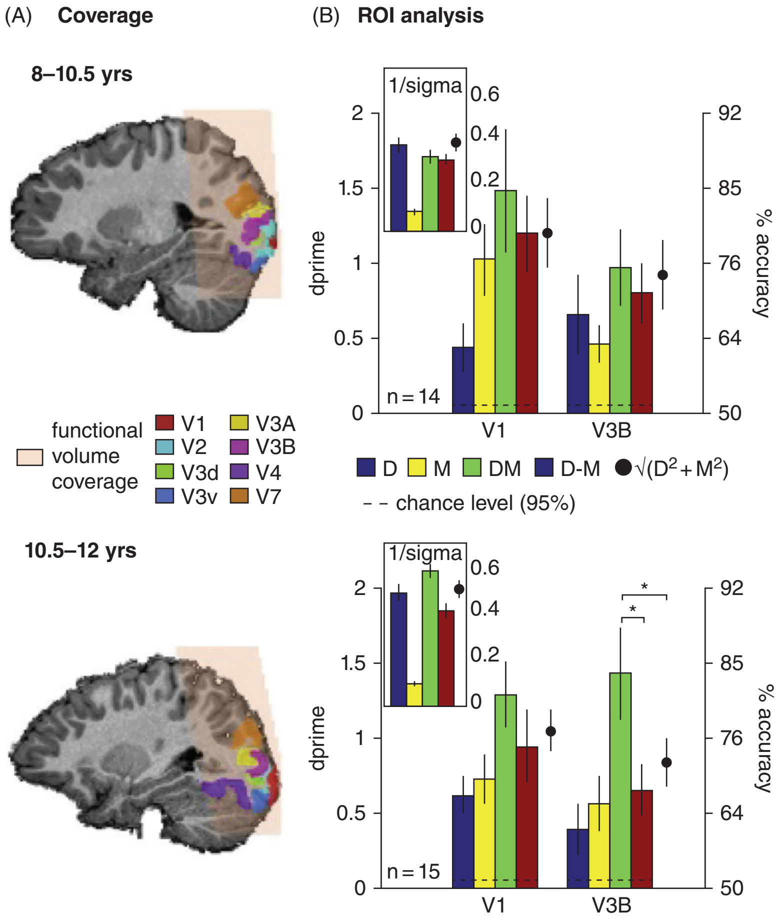


Figure 15.4b Pattern classification fMRI results at different ages. (A) Images depict the scanned brain areas and the regions of interest (ROIs) for two subjects. (B) ROI analysis shows d-prime (accuracy) with near versus far stimulus depth decoded from activation patterns in area V3B. For comparison, the same is shown for area V1. Small bar plots in top left corner represent perceptual performance (1/sigma) of the same subjects—larger values indicate better depth sensitivity. Comparison of 8- to 10.5-year-olds and 10.5- to 12-year-olds shows a change in processing mechanisms, indicating that older children integrate information (fusion). Activation patterns in V3B show that accuracy for congruent cue information exceeds accuracy from conflicting cues as well as single cue predictions.
Source: From Dekker et al. (2015). Adapted with permission.

children use a mechanism by which one sense dominates the other, depending on the task/quality of the stimulus (Gori et al., 2008; Petrini et al., 2014, see Figure 15.5).

The reasons behind the late development of multisensory integration are not quite clear. Gori et al.'s (2008) prominent cross-calibration theory states that, before the process of integration emerges, the senses "teach" each other during perception. That is, the most reliable sense teaches the less reliable sense to process accurately the perceptual properties of objects and people in the environment. As the relative sensory reliability depends on the stimulus properties that are being processed, the task at hand

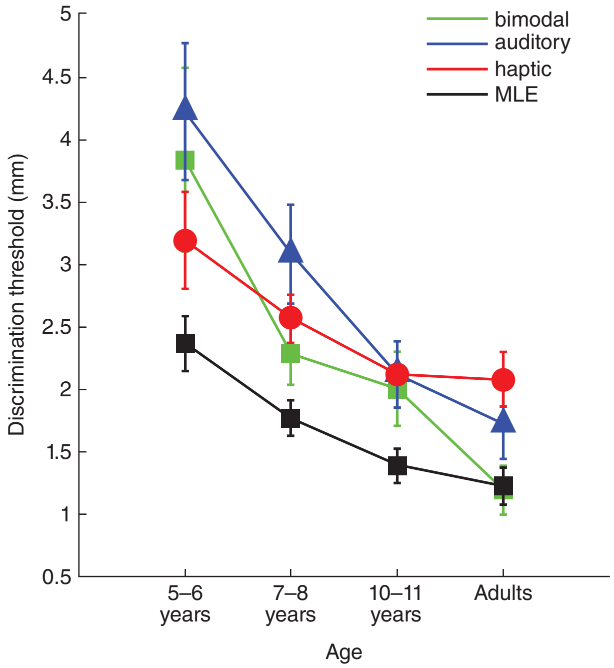


Figure 15.5 Late development of audio-haptic integration measured in a size discrimination task. Mean size discrimination thresholds give the minimum size difference between two stimuli that is required for the observer to tell that there is a difference between them. This means that smaller discrimination thresholds indicate higher precision. The red points indicate the discrimination threshold for observers using touch only (σ_H) whereas the blue triangles stand for the same individuals using hearing only (σ_A). The green squares show discrimination thresholds for the audio-haptic bimodal condition. This experimental data was plotted in comparison to the average MLE model prediction (black squares), which was calculated individually for each subject to predict performance from statistically optimal multisensory integration. The predicted threshold for bimodal size discrimination was calculated using the equation: $\sigma^2_{HA} = \sigma^2_H \cdot \sigma^2_A \,/\, (\sigma^2_H + \sigma^2_A)$. Error bars represent the standard error of the mean.

Source: From Petrini, Remark, Smith, and Nardini (2014). Reprinted with permission.

determines which sense will calibrate the other. For example, when visual and auditory cues are present at the same time, the visual information is weighted more than the auditory information during spatial tasks.

The higher importance of calibration during childhood might be due to a trade-off between optimal multisensory integration and physiological development. Hereby, calibration takes into account that, during early years, children undergo a period of extensive physiological changes. For example, their limbs grow rapidly and the separation and length of eyes increase. These changes must be accounted for by the perceptual systems. Hence, it would be disadvantageous to integrate imprecise, because ever-changing, estimates but beneficial to first refine them in each sensory system alone through cross-modal calibration.

SENSORY AND MOTOR DEFICITS

So far we have seen how perceptual abilities develop and achieve optimality under typical circumstances. We know that, usually, performance is best when all forms of information are present, providing a rich signal. However, as we previously mentioned, there might be situations in which the input from either one sense or several senses is unavailable or is suddenly lost. Blind and deaf individuals lack inputs from important sensory modalities, which in turn greatly affects their quality of life. For example, finding the way home may appear easy to sighted individuals but could be quite a demanding task for blind or visually impaired individuals. Similarly, crossing a road, finding certain objects in unfamiliar places, and participating in conversations to enhance social bonds are further examples of demanding tasks in absence of vision or hearing. It is interesting to note that when one or more sensory modalities are missing or impaired, it becomes much clearer how multisensory perception is essential: in order to cope with the lack of information from the missing sense, the remaining senses have to take primary roles in representing and identifying stimuli in the environment.

Worldwide, there are about 39 million people who are completely blind. Another 246 million people live with some form of visual impairment (World Health Organization [WHO], 2014b). However, it is estimated that 80% of these cases could be prevented or cured. This is because the great majority of people with visual impairment live in developing countries, where treatment of some of the major causes for visual impairment, cataracts and glaucoma, is limited (WHO, 2014b). On the other hand there are about 360 million people worldwide with disabling hearing loss, 32 million of whom are children (WHO, 2014a). People with both forms of sensory impairment are at higher risk of social and emotional discrimination. In 2008, roughly 67% of the UK's registered blind and partially sighted people were unemployed (Royal National Institute of Blind People, 2013), which was much higher compared to the general working age population. This number has even been increasing to about 73% in 2015 (Hewett & Keil, 2015). Moreover, there are existing links between the loss of sight and reduced well-being (Burmedi, Becker, Heyl, Wahl, & Himmelsbach, 2002). Higher risks of depression, for example, might arise from additional difficulties during social interaction. All these risks and difficulties emphasize how severe the economic and socio-emotional outcomes of sensory loss can be to the individual. Therefore, it is important that research tries to develop ways and methods that promote adaptation to the demands of everyday life for people living with sensory impairments. This encompasses the development of understanding how the brain generates perception in the sensory impaired individual, and how neural mechanisms promote this, in order to achieve the best rehabilitative outcome.

Certainly, audition and vision will only be used as examples here, and other forms of sensory or motor impairment can also lead to complication in everyday life tasks. However, until now most research has been focusing on vision and audition, probably making them the best understood sensory systems. As mentioned earlier, vision provides the most reliable information about the nature and position of objects (Chapter 1, this volume), whereas audition does about the temporal aspects of different sensory events (Chapter 2, this volume). Hence, visual and auditory information are crucial for many basic tasks such as orienting and identifying objects in the environment, shifting attention toward important events or for appropriately interacting with others. It is therefore not surprising that deficits in these senses have attracted the interest of researchers worldwide aiming to restore or compensate for these types of sensory loss.

However, in order to develop successful methods and devices that help the visually or hearing impaired in daily life tasks, we first need to understand how the absence of vision or audition affects perception in general and, more specifically, the use of the other, remaining senses.

Effect of Sensory Loss on Other Senses

For a long time, it has been widely accepted that the absence of visual input improves information processing in the remaining senses. This has been supported by research showing that visually impaired individuals display equally good or sometimes even superior performance on auditory localization (Lessard, Pare, Lepore, & Lassonde, 1998; Röder et al., 1999; Voss et al., 2004), tactile discrimination (Alary et al., 2008; Goldreich & Kanics, 2003, 2006), and memory tasks (Amedi, Raz, Pianka, Malach, & Zohary, 2003; D'Angiulli & Waraich, 2002; Pasqualotto, Lam, & Proulx, 2013; Raz, Striem, Pundak, Orlov, & Zohary, 2007), as well as enhanced musical and verbal processing abilities (Amedi et al., 2003; Hugdahl et al., 2004; Pasqualotto, Lam, et al., 2013).

However, an increasing number of studies have come to very contrasting results. Many of them demonstrate that the loss or impairment of visual input affects the way space is perceived in the remaining senses (for a review see Pasqualotto & Proulx, 2012). Auditory localization of objects, for example, has been extensively studied in human and non-human participants (Konishi, 2000; but see Collignon, Voss, Lassonde, & Lepore, 2009 for a review). Clearly, this can be attributed to the central role object localization plays in many independent daily-life tasks and its strong dependence on visual information. Some studies have shown that blind individuals show normal or even supra-normal auditory localization performance in the far space as well as near space, whereas haptic information might drive the calibration of auditory space through sensory-motor feedback in the latter (Fieger, Röder, Teder-Sälejärvi, Hillyard, & Neville, 2006; Lessard et al., 1998; Voss et al., 2004). Other studies found that in early blind individuals the representation of auditory space in the lower sagittal plane is compromised in comparison to sighted individuals (Finocchietti, Cappagli, & Gori, 2015). The authors argued that this might be due to a disruption of audio-visual cross-sensory calibration (Gori, Sandini, Martinoli, & Burr, 2014). Thereby, auditory localization in the horizontal plane would yield accurate results because certain cues, which are used by the brain to decode sound source location—that is, inter-aural loudness difference (ILD) and inter-aural time difference (ITD)—would still provide a reliable location estimate (Moore, 2003). In general, the human auditory system can take advantage of both of these types of information, or each one separately if they are not both present. An advantage of sound localization in the horizontal plane has also been supported by earlier studies (Lessard et al., 1998; Voss et al., 2004). Sound location in the sagittal plane, on the other hand, can only be mapped based on the pinna-related spectral shape cues, which are less accurate than interaural time or loudness differences (Zwiers, Van Opstal, & Cruysberg, 2001). Because vision is usually thought to have a stronger impact on auditory localization in the vertical dimension (Lewald, 2002), and additional visual information is not available in the blind, this may result in poor localization and ultimately disrupted auditory spatial maps.

Further factors like spatial sections of auditory/visual field seem to influence these contrasting outcomes. That is, superior auditory localization performance of blind individuals is mainly observed in the lateral perceptual field but not in the center (Röder et al., 1999). Also, the age of onset of blindness seems to play a critical role. Although, in Finocchietti et al.'s study (2015), early blind individuals showed impaired audio localization in the lower sagittal plane, late blind individuals did not.

This group's responses were similar to those of sighted participants. This might indicate that cross-modal calibration builds up the foundations for understanding physical properties in the environment at an early age, when plasticity is high (Putzar, Goerendt, Lange, Rösler, & Röder, 2007).

Other studies have examined the cross-modal effects of visual deprivation on somatosensory processing. Although blind individuals are often referred to—and reported to—have superior tactile acuity (Goldreich & Kanics, 2003; Norman & Bartholomew, 2011), there is also evidence of an impairment of haptic recognition and orientation discrimination abilities (Gori, Sandini, Martinoli, & Burr, 2010; Pasqualotto & Newell, 2007). However, the effects of visual deprivation on multimodal processing have been less intensely investigated. In a recent study Guerreiro et al. (2015) compared neural responses of sighted participants in an audio-visual task to those of participants, who were blind at birth but regained sight following surgery within the first 2 years of life. Using functional magnetic resonance imaging the authors found that early blind, sight-restored individuals did not exhibit multisensory integration of audio-visual cues (Guerreiro, Putzar, & Röder, 2015). From this they concluded that early visual experience lays the anatomical and functional foundations for audio-visual multisensory integration in later life. The idea of developmental periods during which perceptual learning is enhanced, indeed, is not new and many studies have looked at (perceptual) learning in the light of heightened neural plasticity during early life.

The concept of neural plasticity comprises the ability of the central nervous system to adaptively modify itself in its own structural and functional organization on the single cell level (Ahissar et al., 1992; Bach-y-Rita, 1988). During learning, for example, neural plasticity allows the central nervous system to adapt to functional needs. In terms of perception, this structural and functional reorganization is driven by individual, perceptual experience that often is of multimodal nature. During an individual's development there appear to be time windows of high neural plasticity, called sensitive periods (Knudsen, 2004). Sensitive periods are more likely to occur when organisms are uncertain about environmental conditions or are not constrained in their phenotype-environment match (Fawcett & Frankenhuis, 2015). Because babies can be born into all different types of environments and are not prenatally adapted to a certain one, this would explain why most sensitive phases happen very early during development. During these periods perceptual experiences have stronger influence on the brain in form of structural and functional changes. Early studies on animals have shown that the experiences within these sensitive periods, during which the individual learns to recognize certain aspects of its environment (e.g., its parents; Hess, 1972; Lorenz, 1937), cause a long-lasting effect on the individual's behavior (Immelmann, 1972). Learning that occurs during this time period, therefore, "lays the foundation for future learning" (Knudsen, 2004, p. 1412). So what does this mean for sensory deficits? What does the brain do in order to gain a reliable percept of the environment when input from one sensory modality is not available during phases of heightened plasticity?

Compensation of Sensory Loss Through Reorganization

People who lose one sense due to disease or damage of the sensory organs (e.g., retina in the visual system, cochlea in the auditory system) do not necessarily lose the capacity to perceive or process stimuli that are usually derived from these sensory modalities

(Bach-y-Rita & Kercel, 2003). In case of sensory input absence, the central nervous system responds with neural plasticity to functional needs. The increased use of the remaining senses requires structural reorganization in the intact cortical areas of these senses. For example, blind experienced Braille readers have enlarged cortical regions in the somatosensory cortices representing their "reading" finger (Pascual et al., 1993). Further, cortical auditory areas are larger in blind than in sighted individuals (Elbert et al., 2002), which is also reflected at the behavioral level in an enhanced ability to process language or music in the blind. These, among numerous other examples, show that structural and functional reorganizations of the brain imply various benefits for the individual as they allow for a better use of sensory information derived from the remaining senses. At the same time, however, neural reorganization can also bear potential negative consequences, especially for cases in which senses are restored after a long period of deprivation (Fine, 2008). We will discuss the effects of sensory loss/deprivation duration on the functional outcomes of restoration later in this chapter.

The findings we mentioned previously do, however, not answer the questions of how cortical visual areas in blind or visually impaired (or cortical auditory areas in hearing impaired) individuals get structurally and functionally reorganized. Will these areas deteriorate or will they reorganize to take over the processing of different sensory information? There is growing experimental evidence that early visual deprivation does not lead to inactivation of the visual cortex, but that it is, in fact, followed by structural and functional cortical reorganization allowing auditory or somatosensory information to be processed in this area (Amedi et al., 2003; Cohen et al., 1997; Collignon et al., 2015; Collignon, Lassonde, Lepore, Bastien, & Veraart, 2007; Fine et al., 2003; Théoret, Merabet, & Pascual-Leone, 2004 but see Noppeney, 2007 for a review). This reorganization constitutes a compensation for visual loss through the enhanced processing of auditory and somatosensory information in presumptive visual areas. Indeed, several studies have shown that activation of the visual cortex in the blind is associated with sound and language processing, spatial imagery, as well as Braille reading and tactile discrimination (Cohen et al., 1997; Kupers et al., 2006; Struiksma et al., 2011; Uhl, Franzen, Lindinger, Lang, & Deecke, 1991; Vanlierde, De Volder, Wanet-Defalque, & Veraart, 2003). However, functional and structural cortical reorganization is not specific to blindness but extends to other sensory modalities and lack of such. For example, Levänen et al. (1998) made observations about the auditory cortex of a congenitally deaf adult being actively involved in the processing of somatosensory information (Levänen, Jousmäki, & Hari, 1998). Interestingly, many studies reported noteworthy differences in information processing and reorganization between individuals who became blind at a very early age (or who were blind from birth), and those who went blind later in life (see Noppeney, 2007). This may indicate that enhanced neural plasticity during childhood influences the brain's susceptibility for reorganization. It further highlights that the availability of sensory input critically determines the way in which our brains process sensory information and ultimately perceive the world.

The Role of Action

Surely, plasticity forms the basis of learning to perceive any form of sensory input, at least at the neural level. However, as we have discussed earlier, perception and action are critically interwoven and their self-calibrating nature plays an important role in the proper development of ecologically relevant motor skills and the ability to perceive and interact with objects in our environment (Proulx et al., 2015; Proulx, 2010). To achieve a reliable representation of objects, haptic perception depends largely on perceptual (inter-sensory) as well as action-perception (motor-sensory) processes. Whenever a motor action is carried out, the CNS sends efferent motor commands to the actuator (e.g., hand muscles). At the same time, a copy of these motor commands is generated and matched with the afferent tactile and proprioceptive sensory feedback (Von Holst & Mittelstaedt, 1971). Integration and comparison of these two strands of information generate a specific haptic feedback and allow our brains to predict physical properties of the environment we interact with. However, this reafference process really becomes important and improves haptic perception later in development (Gori et al., 2012). In typically developing children, who still undergo rapid physiological changes, internal motor command copies are more likely to be noisy. This might explain why haptic precision has been found to only reach adult-like levels early in adolescence (Gori et al., 2012).

However, the strong relationship between haptic perception and physical action emphasizes that motor impairment should not be neglected when discussing perception in the light of sensory deficits. More generally, motor impairments are characterized by the total loss or limitation of function in a body part and can be, just as any sensory impairment, of diverse nature. Often, motor impairments can be caused through complications during birth or genetic conditions. Further potential causes, which occur later in life, are accidents or diseases like polio or tuberculosis. According to the CDC's Autism and Developmental Disabilities Monitoring Network, cerebral palsy has been found to affect 1 in 323 children in the United States in 2008 (Christensen et al., 2014). It is, therefore, thought to be the most common motor disability in childhood (Accardo, 2008). Furthermore, altered haptic perception is reported in other childhood disorders like autism spectrum disorder (Gowen & Hamilton, 2013) or language impairment (Muursepp, Aibast, Gapeyeva, & Paasuke, 2012). Also, Parkinson's disease and multiple sclerosis are common causes of motor impairment. The high prevalence of these conditions has major implications not only for the improvement of motor system health resources but also for the intact functioning of sensory perception in individuals with motor impairments. Just like perception cannot properly function without motor actions (e.g., through feeling the texture or shape of surfaces, scanning an objects properties with the eyes), action heavily depends on sensory feedback. These two systems shouldn't be considered as independent components but rather as interwoven parts in a holistic action-perception-framework (Ernst & Bülthoff, 2004).

SENSORY AND MOTOR AIDS AND REHABILITATION TECHNIQUES

When thinking of sensory rehabilitation, we often think about the restoration of the impaired sense, which can be accomplished by, for example, surgical procedures or restoration therapy. However, rehabilitation can also be conducted through the remaining, intact senses via sensory substitution. The following sections give an overview of procedures and technologies that are currently available for people with visual and auditory impairments.

A number of useful assistive technologies like force-feedback devices (Zhu, Kuber, Tretter, & O'Modhrain, 2011) have been developed for blind users to navigate through the web. Generating haptic feedback via affordable gaming devices like the Novint Falcon or a mouse with motor feedback and adding auditory feedback enables blind and visually impaired people to explore usually vision-dominant computer programs like Excel or online websites through touch and hearing (Doush, Pontelli, Simon, Son, & Ma, 2009; Oyamada, Bidarra, & Boscarioli, 2013). Multisensory virtual environments that use touch and sound have further been used to convey geographic information to visually impaired users (Jacobson, Kitchin, & Golledge, 2002; Lahav, Schloerb, Kumar, & Srinivasan, 2012; Lawrence, Martinelli, & Nehmer, 2009). For the hearing impaired and deaf, there are also a number of aids like Silent Call systems, which use different portable radio frequency transmitters to inform the user about incoming telephone calls, doorbells, smoke or carbon monoxide detectors, door or window access, and other events that are relevant in everyday life. Users can receive signals of these events in the form of pager-like vibrating receivers or flashing strobe light. However, these technologies and aids have a limited impact on everyday activities and the overall quality of life of blind, deaf, or partially blind and deaf individuals. For example, one of the most demanding tasks for a blind or partially blind person is to navigate the environment and find his/her own way in it.

Navigating from one location to another poses one of the major, daily challenges to people who cannot accurately perceive their environment through vision. From reading bus signs, street names or maps, to looking out for cars, obstacles, traffic lights, or even other people—the world in which we navigate and the way in which important information is transferred is often not designed for visually impaired or blind people. They frequently have to rely on their remaining senses, and therefore a lot of the information is simply not accessible to them. In 2014, Microsoft, Future Cities Catapult and Guide Dogs Association teamed up to tackle some of the mobility challenges people with sight loss face. As part of their collaborative project Cities Unlocked (Future Cities Catapult, 2016), they introduced a navigational headset that helps blind and visually impaired users to find their way through the city. The system relies on GPS information and a network of Bluetooth beacons installed and placed around the city. In this way the system combines the advantages of common navigation systems (e.g., turn-by-turn directions) with information about nearby points of interest or transportation updates. Compared to a normal navigation system, the headset uses audio guidance that is played through a headset that transmits sounds in form of vibrations through the upper jawbone, thereby leaving the ears uncovered and able to listen out for sounds in the environment. The system has been launched and tested in 2014 with eight participants, half of whom were totally blind and the other half having some sort of residual vision. The subjects had to travel between London's Paddington train station and Reading, using different forms of public transport as well as navigating through urban environment. However, in addition to this navigation tool, users had still to rely on further mobility aids like guide dogs, white cane, or some residual vision, because GPS or online information cannot effectively communicate certain types of information such as the presence of obstacles, cars, and other people.

To increase independence and mobility, it is necessary to facilitate direct interaction with the environment, may it be obstacle detection and avoidance or identifying and understanding people. With this in mind, a number of new sensory rehabilitation aids have been developed thanks to the recent technological advances. We will first look at sensory restoration techniques with focus on the visually impaired and give a short description of techniques for the hearing and the motor impaired. We will then introduce sensory substitution devices as a means of perceiving and interacting with the environment through the remaining intact senses.

Visual Restoration

Our increasing understanding of sensory mechanisms and processing principles as well as the vast improvement of technology have opened new opportunities in the field of sensory rehabilitation (for a review see Maidenbaum, Abboud, & Amedi, 2014). One way to restore vision in the blind through direct surgical procedures. Cataract surgery is the most commonly performed operation these days. This includes the replacement of the affected, clouded lens with an intraocular implant, a small plastic lens. Other approaches include using non-invasive technology that converts images into auditory or tactile displays (Proulx, Brown, et al., 2014; Proulx, Ptito, & Amedi, 2014). How might visual restoration be assessed? Visual acuity provides a measure of the distance at which two points are resolvable. Typically, optotypes in the form of letters or shapes are presented with decreasing size to determine acuity expressed as a Snellen fraction. The Snellen fraction is the ratio of the testing distance to the distance at which the smallest recognizable optotype subtends 5 arc-minutes, or 0.083 degrees.

Techniques like artificial retinal prostheses (da Cruz et al., 2013; Humayun et al., 2012; Zrenner, 2010) or the transplantation of photoreceptors (Yang et al., 2010) that aim to physically replace or bypass the damaged parts of the peripheral visual system offer treatment for people who lost vision through retinal damage (e.g., age-related macular degeneration).

Over the last couple of years, new methods involving treatment with embryonic stem cells have been developed (Schwartz et al., 2014). This treatment is thought to restore vision through the repopulation of damaged retinal cells or the prevention from further degeneration of the cells. Stem cells are of special interest because of their ability to self-renew and their high plasticity, allowing for very individual and specialized application.

At the moment, however, the most common restoration approaches require retinal implants (for a review of some of the current models see Chuang, Margo, & Greenberg, 2014; for a more general review see Dagnelie, 2012). There are a couple of different retinal implants available; however, only two of them are currently CE certified, and only one of them has US Food and Drug Administration (FDA) approval.

One of these retinal prostheses is the Argus II (Second Sight; Ahuja et al., 2011; da Cruz et al., 2013; Humayun et al., 2012; for a review see Luo & da Cruz, 2015), which is aimed at people with a malfunction of the photoreceptors (e.g., retinitis pigmentosa). This device includes an external digital camera, integrated into the frame of eyeglasses, to capture images of the user’s environment, an image processor, which converts the images into instructions that are sent to the retinal implant via a wireless antenna. These signals trigger the implanted array of 60 electrodes to emit small electrical pulses, thereby stimulating the remaining retinal cells that transmit electrical impulses to the brain via the optic nerve. The brain then uses the transmitted visual information to create light pattern perceptions that can then be learned by patients through training. With this prosthesis, users have been shown to achieve a visual acuity of up to 20/1262 (Humayun et al., 2012) within a visual field width of 20 degrees.

The second device currently available is the Alpha IMS subretinal implant (Retina Implant AG; Zrenner, 2002), which consists of an electronic wireless microchip that captures light falling onto the retina and stimulates the optic nerve, which then in turn delivers the signal to the brain. The microchip features a 1500-pixel resolution and allows for seeing black and white images. Unlike other retinal implants, no external camera is needed to capture the visual image. Studies reported that the highest acuity that humans implanted with this chip reached was 20/546 (Chuang et al., 2014) within a visual field of 15 degrees.

Visual acuity alone is not necessarily a sufficient measure of visual rehabilitation. In a recent study (Haigh, Brown, Meijer, & Proulx, 2013), using a sensory substitution device as an auditory display of images (described in more detail later in this chapter), it was found that measuring visual acuity within sensory rehabilitation must consider additional variables taken for granted in normal acuity testing, such as consideration of the field of view provided by the technique. Hereby, one would still be classified as visually impaired if restricted by severe tunnel vision (these issues are further explained at www.seeingwithsound.com/acuity.htm).

As for retinal implants, the resulting visual acuity and size of the visual field are determined by the amount and density of electrodes which emphasizes that there are biological limits constraining the success of this form of technology (Chuang et al., 2014). It is important to note that there are currently physical limitations on the best visual acuity possible through all kinds of rehabilitation methods, not only restorative.

In a 3-year clinical trial that followed 30 individuals who received the Argus II visual prosthesis, Ho et al. (2015) found that the implant allowed subjects to perform basic visual functions like object localization or identifying motion direction and increased visual acuity (Ho et al., 2015). An earlier trial reported similar findings, showing that subjects were able to even identify letters and words (da Cruz et al., 2013). Interestingly, they also found that the age at transplantation is an important predictor for outcome success of visual restoration. However, this does not reveal if patients really benefit from the additional, visual information in more complex tasks. As discussed earlier, one of the most demanding task for visually impaired individuals is navigating and finding their way in the environment. Humans typically use visual cues to navigate, as well as self-motion information (Souman et al., 2009). A recent study by Garcia et al. (2015) investigated how well patients, who have been implanted with the Argus II visual prosthesis, could make use of the new, visual spatial information to increase navigational precision. They tested four Argus II implanted patients and sighted individuals on a path reproduction and a triangle completion task, both in the absence and presence of an indirect visual landmark. Sighted participants wore goggles that only allowed a restricted field of vision and low visual resolution, mimicking the visual field and resolution properties provided by the Argus II. The information from the visual landmark that was received by the sighted participants was sufficient to increase navigational precision. In Argus II patients, however, there were no such improvements in the path reproduction task (see Figure 15.6). Two patients showed a benefit similar to normally sighted subjects on the triangle completion task. However, compared to their sighted counterparts, navigational precision in general was higher in patients when visual cues were absent. This indicates that, when individuals have

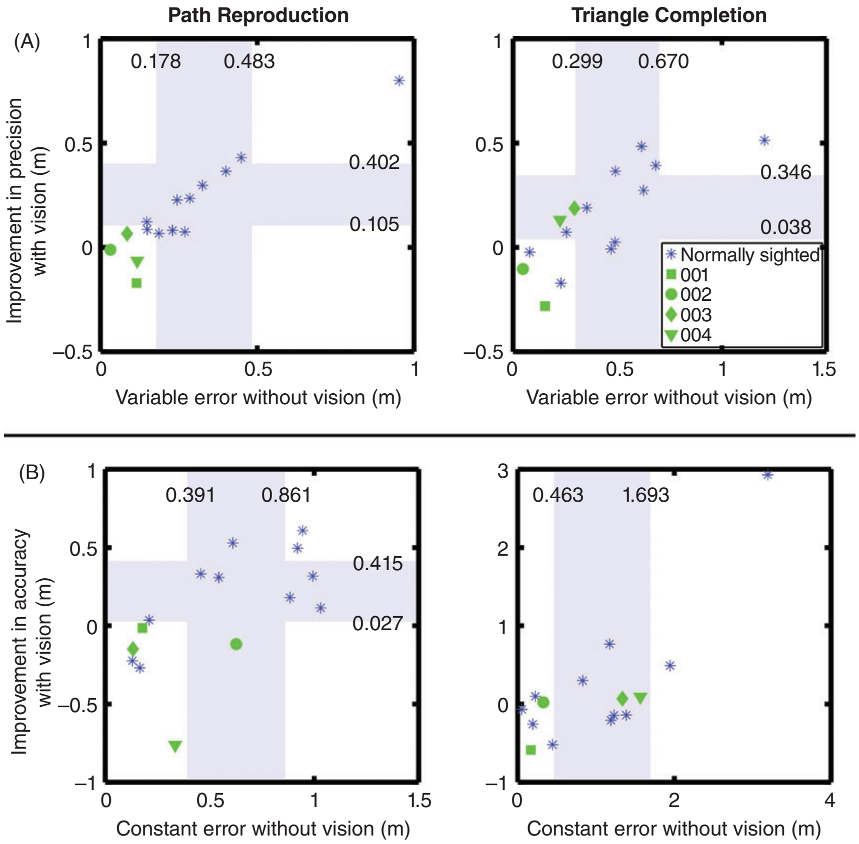


Figure 15.6 Performance of four patients implanted with a visual prosthesis (green symbols) and sighted individuals (blue stars) on a path reproduction (left) and a triangle completion (right) task. Sighted participants wore goggles that resembled the visual properties provided by the Argus II. All participants were tested in the absence and presence of a visual landmark. Depicted is the improvement of navigational precision with variable error (A) and accuracy with constant error (B) between trials where a visual landmark was absent or present. The shaded region represents the 95% confidence intervals computed from the performance of sighted individuals. Information from the visual landmark was sufficient to increase navigational performance during path reproduction in sighted participants, but not in patients using the visual prosthesis. All patients showed a lower variable error when navigating without vision compared to normally sighted individuals. Two of four patients improved in precision on the triangle reproduction task in a similar way to sighted participants. Also, these two patients had lower constant errors without vision compared to controls.
Source: From Garcia et al. (2015). Reprinted with permission.

been blind for many years and nonvisual information becomes more reliable, visual information provided by the Argus II retinal prosthesis might not be sufficient to increase performance on navigational, spatial tasks for which sighted individuals usually use vision. This also supports the notion that age of blindness onset and age of implantation (that is, how long an individual uses nonvisual information for visual dominant tasks), coupled with the quality of visual information, have an impact on the effectiveness of visual restoration devices.

Auditory Restoration

Cochlear implants are targeted at deaf or hearing-impaired people and work in similar ways to the retinal implants. Unlike regular hearing aids, however, which amplify sounds in order to be detected, cochlear implants transmit sound information via a microelectrode array that, instead of stimulating the receptors in the inner ear, sends signals directly to the auditory nerve. People with auditory nerve damage can benefit from auditory brainstem implants (Jackson, Mark, Helms, Mueller, & Behr, 2002; Rauschecker & Shannon, 2002), which directly stimulate cells in the brainstem that are connected to further auditory processing areas. Cochlear implants have been around for more than 40 years now and have undergone constant development and improvement from single- to multi-electrode devices that allow complex digital processing of auditory signals (Møller, 2006). The time of implantation has been shown to play a critical role for the hearing outcome success. Sharma and colleagues (2002) found that congenitally deaf children who have received cochlear implants before the age of 3.5 developed normal, age-appropriate latency responses in the auditory cortex (Eggermont, Ponton, Don, Waring, & Kwong, 1997). Children who received the implants later in childhood showed delayed cortical responses, with maximal delay of about 100 ms at the age of 7 and older (Sharma, Dorman, & Spahr, 2002). This indicates that auditory (sensory) restoration may work best at an earlier age, when the brain shows maximum plasticity.

The cochlear implant is considered to be the world's most successful neural prosthesis. Therefore, it is not surprising that a lot of research in hearing impairment focuses on the improvement and further development of this device. Unfortunately, there is not at the moment a visual rehabilitation technique as successful, as evidenced by the development of a widespread of methods and a more sparse research effort.

(Sensory-)Motor Restoration

As discussed earlier, cerebral palsy is the most common motor impairment in children and results in paralysis through motor pathway injuries or abnormal brain development. However, other conditions like spinal cord injury, multiple sclerosis, amyotrophic lateral sclerosis, or muscular dystrophy might affect the motor system and result in limited controlled motor actions. Besides surgical procedures like nerve transfer and free muscle transfer, bioelectrical interfaces have increasingly gained popularity for restoring motor function (Langhals, Urbanchek, Ray, & Brenner, 2014). The latter use direct, neural interfaces to record and electrically stimulate muscles or nerves. Thereby, degenerated or damaged muscles and neural structures can be bypassed to send motor commands from the central nervous system to the biological or artificial actuator.

Research on these so-called neural interface systems (NIS) has progressed quickly in the past years (for a review see Donoghue, 2008). NIS usually encompass three major components: a neural sensor that detects the signals, a processing unit that decodes the neural signals and translates them into useful commands for the third component, which, in turn, can be any technological (Donoghue, Nurmikko, Black, & Hochberg, 2007) or biological (Bouton et al., 2016) system capable of executing motor functions (e.g., assistive technologies like computer desktops, motorized wheelchairs, robotic limbs, or a patient's own limb if the neural but not muscular part of the motor system is impaired). This makes it especially interesting for individuals suffering from serious conditions like amyotrophic lateral sclerosis or even locked-in syndrome. Investigations and developments in the field of neurotechnology for the motor impaired have increased very quickly in recent years, and have produced technologies like the BrainGate intracortical NIS (Donoghue et al., 2007) or a closed-loop hand prosthesis, which does not only enable motor signals to be executed but also receives sensory feedback from haptic manipulation of objects (Raspopovic et al., 2014; for a review see Ciancio et al., 2016). The latter combines a hand prosthesis, used to enable the execution of motor commands, with concurrent stimulation of the peripheral nerves to achieve real-time sensorimotor feedback. At this point, it might be important, though not entirely surprising, to note that the quality of life is strongly compromised in individuals who suffer from limb amputation (Martinet et al., 2003). This relates especially to the physical inability to conduct certain behaviors, to increased pain, and to reduced energy levels. Enabling amputees to conduct behaviors involving prostheses, therefore, depends upon the perception of haptic information in order to facilitate action planning and calibration during physical interactions. That is, during motor actions sensory feedback allows for a fine force control of physical agents (e.g., fingers, hand) and, therefore, enables us to manipulate objects in a very specific way. Sensing object properties facilitates identification as well as grasping and handling of objects and emphasizes the importance for sensorimotor recalibration in our everyday life. Therefore, providing both motor control and consequential sensory experience has been the aim for many technological developments that try to implement a functional equivalent to biological limbs (Ciancio et al., 2016). A laboratory trial with the prosthesis from Raspopovic et al. (2014) showed that the subject was able to localize the position of an object on the prosthetic hand and apply the most appropriate grasp with an accuracy of 97%. Object consistence recognition and shape identification were successfully conducted with 78.7% and 88% accuracy, respectively (Raspopovic et al., 2014).

Despite these very promising results, the techniques used for motor restoration are still not fully matured and call for improvements in soft- and hardware issues like the flexibility of motor control algorithms and the simultaneous and independent control of multiple agents (Ciancio et al., 2016).

Sensory Substitution

Sensory substitution devices (SSD) for people with sensory impairments provide information about various physical features and dimensions of objects by stimulating the intact senses (Bach-y-Rita & Kercel, 2003; Meijer, 1992; Proulx, 2010). In comparison to sensory restoration using implants or prostheses, this group of sensory aids offers a non-invasive and cheaper alternative. They aim to increase the blind/deaf users' independence and mobility by enabling them to "see through the ears or skin" or "hear through the eyes or skin" objects and people around them, thereby enabling them to engage in direct and dynamic interaction with the world (for a video demonstration see Proulx, 2014).

Some well-known and rather low-tech examples of sensory substitution are Braille reading or the long cane, which both use tactile and proprioceptive input (Bach-y-Rita & Kercel, 2003; Sadato et al., 1996). They have received a great level of interest within and even outside the blind and visually impaired community and are probably the most widespread tools used to substitute vision. Nowadays, there is an increasing number of books, maps, and even atlases available for people who can read Braille. Different types and sizes of white canes allow for more individual assistance when navigating in the environment and reacting dynamically to obstacles and physical landmarks.

This group of more traditional techniques and devices has been extended by modern SSDs that benefit from the increasing use and development of technology. These modern SSDs can be subdivided into three main components: an input sensor that captures the information from the environment (e.g., visual scene), a processing unit that converts the input signal into another signal (e.g., sound representing the visual scene), and a human machine interface that transmits the converted information to the biological sensors of the user's substituting sensory system (Maidenbaum et al., 2014).

The first sensory substitution device using modern technology and artificial sensory receptors was introduced by Bach-y-Rita and colleagues in 1969 and transferred visual spatial information to the user via tactile stimulation of the skin. This Tactile Visual Substitution System (TVSS) used an array of 400 tiny tactile stimulators, which were embedded into the back of a dental chair to transmit information captured by a video camera that was mounted on a tripod adjacent to the chair (Bach-y-Rita, 1996/2002). The captured images were transduced into vibration patterns, which stimulated the skin on the back of the participants. Bach-y-Rita was convinced that exploiting the advantages of the brain's plasticity would enable blind users to learn seeing with their skin. He, and his colleagues, trained blind subjects with the TVSS to recognize simple patterns like lines and circles and later even complex objects they encounter in everyday life like telephones or chairs. They found that participants were able to "discover visual concepts such as perspective, shadows, shape distortion as a function of viewpoint, and apparent change in size as a function of distance" (Bach-y-Rita, Collins, Saunders, White, Scadden, 1969, pp. 963–964). Also, the device enabled a congenitally blind person, who was trained with the system for only 25 hours to "see" the outlines of a candle's flame (Guarniero, 1974).

However, vision might have some special properties that are challenging to convey to the other senses. How well visual images can be transferred is strongly influenced by the processing capacity of the receptive system (Kaczmarek, Webster, Bach-y-Rita, & Tompkins, 1991). A substantial body of work, much of it inspired by Treisman's Feature Integration Theory (Treisman & Gelade, 1980), has established the role of parallel processing in vision. That is, multiple features, and even multiple objects, can be processed simultaneously to a certain extent in vision. The nonvisual modalities, in particular haptics, are instead often characterized by sequential or serial processing (Henriques & Soechting, 2005; Hsiao, Lane, & Fitzgerald, 2002). For example, when we explore an object with our hands we only get an idea of its shape by integrating the information we sample over time through moving our hands across the object's surface. During visual processing, on the other hand, we can determine the object's shape in an instance by simply looking at it. This contrast was made clear in an experiment that tested sighted participants by reducing the visual field with tunnel vision. This forced subjects to acquire information in a serial manner (i.e., by sampling only small areas at a time), and thus made visual object recognition performance equivalent to haptic object recognition (Loomis, Klatzky, & Lederman, 1991; Rieser, Hill, Talor, Bradfield, & Rosen, 1992). A recent review described how developmental vision has a special role in conveying information in parallel (Pasqualotto & Proulx, 2012). This is a key ability that is crucial for the integration of multisensory cues that are available within a close spatial and temporal time window and, hence, for perception and learning (Proulx, Brown, et al., 2014).

Sensory processing of spatial characteristics is furthermore determined by the density of sensory receptors. In touch, for example, skin sensitivity varies with the amount and density of mechanoreceptors and is lowest in the back and highest in the face and tongue. Researchers therefore modified the TVSS into a version, which is known as the BrainPort today. This device, instead of mechanically stimulating the skin on the back, uses electro-tactile impulses to stimulate receptors on the surface of the tongue (Bach-y-Rita et al., 1998, see Figure 15.7). Besides gaining higher resolution, this also reduces energy requirements due to lower stimulation voltages and, therefore, allows for better portability.

The BrainPort consists of a flexible electrode array that is placed in the mouth to stimulate the receptors of the tongue (Sampaio, Maris, & Bach-y-Rita, 2001). This array connects to a tongue display unit (TDU; Kaczmarek, 2011), which receives input from a head-mounted video camera and converts the visual image into a tactile image. Afterwards, the latter is passed on to the electrode array via a ribbon cable, stimulating the tongue's receptors. Blind users of this device can then learn to interpret the patterns generated as physical objects in their environment.

Usability of the BrainPort for travel and obstacle avoidance has just recently been assessed, showing that, when given enough time, individuals that use this device to navigate through their environment are able to

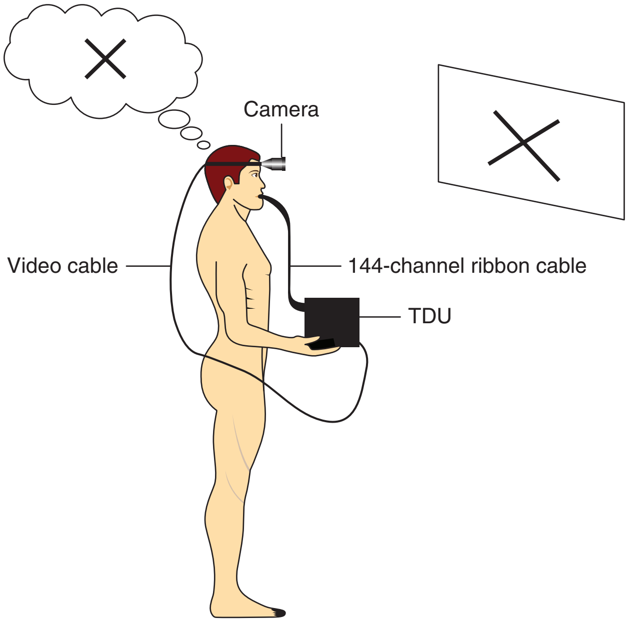


Figure 15.7 Schematic of a tactile-vision sensory substitution system. The system consists of a camera, mounted on the head of the user, which is used as an input device to capture images in the environment. The images are then transmitted to the tongue display unit (TDU) via a video cable and converted into a 144-pixel image which is in turn translated into a pattern of low-voltage pulse trains. This pattern is then transmitted to a flexible electrode array placed on the tongue, where it then stimulates electro-tactile receptors, recreating a tactile image of the environment.
Source: From Bach-y-Rita and Kercel (2003). Reprinted with permission.

accurately detect obstacles (Kaiser, 2004). Furthermore, confidence and performance increased in people with vision loss but not in congenitally blind users when traveling with the device. Perceived independency did, however, not increase. Kaiser noted that to successfully navigate independently through the environment, a high amount of training is essential. An important limitation of the BrainPort is that it only shows color contrasts, which makes it harder for the user to distinguish shadows from obstacles or, for instance, a hole in the ground (Kaiser, 2004). Due to nature of the human machine interface of the TVSS device, stimulating the somatosensory system, this type of SSD would also benefit deafblind people, who constitute a group that has been greatly neglected so far.

Compared to the somatosensory system, the auditory system provides a higher spatial acuity and capacity for parallel processing, which makes the latter system a more efficient means to translate and substitute visual information (Proulx, Brown, et al., 2014). Up to now, a number of general-purpose visual-to-auditory SSDs have been developed. Peter Meijer invented the first of these systems, called "the vOICe," in 1992. The input sensor of this sensory substitution device is a regular video camera, which can be a head-mounted camera covertly integrated into video sunglasses or even a regular smartphone camera. The processing unit can either be a laptop, smartphone, or any other portable device that runs the software, which can be downloaded for free and is therefore accessible for people all over the world. The algorithm converts visual images into sounds by scanning the image from left to right while transforming each pixel into a different sound. Thereby, brightness of the pixel is coded in loudness (i.e., amplitude), whereas its location in the vertical plane is represented by frequency (i.e., pitch), with increasing frequencies toward the upper parts of the image and decreasing frequencies towards the bottom (see Figure 15.8). Due to this translation of visual information into sound, the spatial topography of the image is preserved, giving the user information of their environment that can usually only be assessed visually. The product of this transformation is called soundscape and is transmitted to the user via stereo headphones (an online demonstration can be found in Hadnett-Hunter, Brown, & Proulx, 2015).

The preservation of visual spatial topography of the image makes visual-auditory SSDs a suitable tool for learning the mapping of space in an allocentric reference frame. Reference frames are a prominent feature in spatial navigation and are characterized by the individual learning to interpret the distances and positions of objects relative to one another to create spatial maps of their surrounding. Allocentric spatial maps can be used independently of the position of the own body and, therefore, accessed from different places and orientations in space. Recent studies by Pasqualotto and colleagues showed that congenitally blind individuals use a different, egocentric reference frame for spatial representation compared to sighted and late-blind individuals (Pasqualotto & Proulx, 2012; Pasqualotto, Spiller, Jansari, & Proulx, 2013).

To find out if users could really learn to access information about an object's location (where) and nature (what) by practicing with this SSD, Proulx, Stoerig, Ludowig, and Knoll (2008) blindfolded some of their participants for a period of either 10 or 21 days continuously and let them train with the vOICe at home. The first experiment assessed localization by asking the subjects to locate and press an illuminated touch-sensitive red LED target in an array of 165 LEDs. The participants indicated when they were ready to start a trial, which triggered one of the red LEDs to light up and a buzzing, but location-unrelated, sound to be emitted. The subjects then had

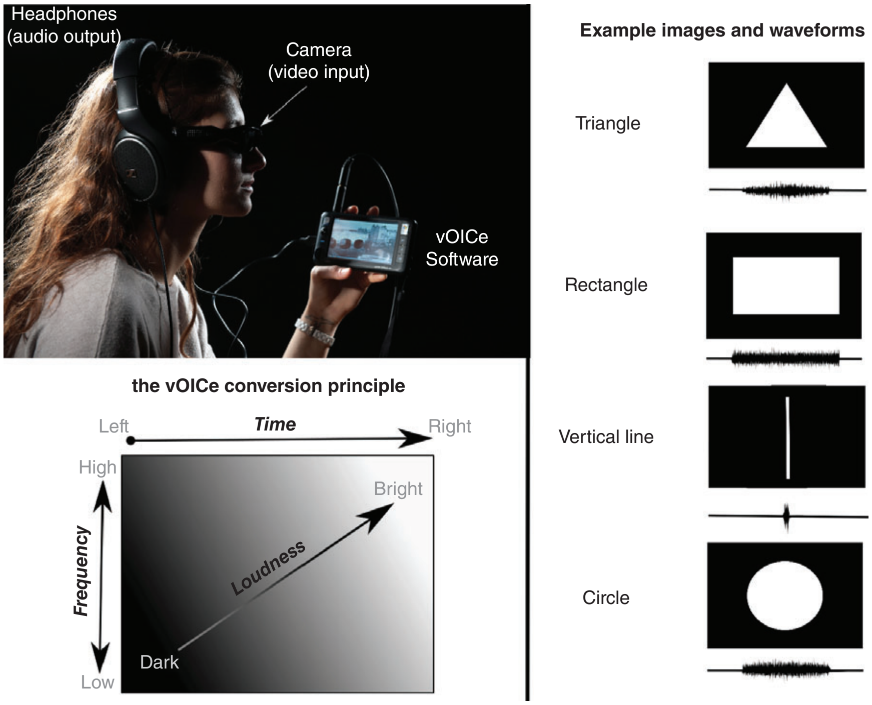


Figure 15.8 An illustration of the vOICe sensory substitution device and its underlying conversion principles. Top left: A camera, hidden in "spy" glasses, is used as an input device to capture video images in the surroundings. The images are then transferred to a processing unit that runs the vOICe software to translate visual images into auditory "soundscapes." These soundscapes are played back to the user via a pair of headphones. Bottom left: Conversion principles of the vOICe. First, the image is converted into grayscale and then scanned from left to right. Objects that appear left in the image are played back early in the soundscape and louder to the left than the right ear. Objects on the right side of the image are played back later and louder to the right than the left ear (time and stereo panning). Objects that are positioned high in the image are translated into high pitch sounds, whereas objects that are low in the image are sonified with low pitch sounds. Brightness is converted into sound amplitude (loudness)—that is, the brighter an object, the louder the sound. Right: Example conversion of four different shapes and their corresponding soundscape images and waveforms.

to find the illuminated LED using the vOICe SSD and press it. When the correct LED was pressed, both light and sound were extinguished, thereby notifying the subject they found the target. Over the three-week period, participants that were using the vOICe in daily practice with natural objects in natural environments (their own homes) were able to generalize that experience to the lab test with significant improvements in speed and accuracy. A second experiment examined the localization and grasping of natural objects placed on a large table (Auvray, Hanneton, & O'Regan, 2007). Again, the authors found successful transfer of experience in the home to the lab, where those trained to use the vOICe showed significant improvement in not only locating the objects but reaching with grasp-appropriate hand configurations. This suggested that they not only understood where the objects were, but had access to features related to what the objects were, too: size, shape, and orientation.

More recent work with the vOICe by Brown, Macpherson, and Ward (2011) found that the location of the camera providing visual input interacted with the goal of the task. For example, while Proulx and Harder (2008) used a head-mounted camera to mimic eyesight, Auvray et al. (2007) used a handheld camera for their tasks. Brown and colleagues (2011) compared the performance for tasks requiring either object identification or localization with both camera positions. They reported an interesting dissociation: Object identification was better with the handheld camera and localization was better with the head-mounted camera. This suggests that the ability to sample many viewpoints of the object via the hand is particularly useful for identifying it, and also that mimicking the normal perceptual-motor contingencies used in localization can improve performance as well, with the viewpoint near the eyes.

This clearly brings another aspect into focus—that is, manipulation of the perspective with the device through self-induced action. The opportunity to manually change the viewpoint of the device establishes a link between vision-substituted (i.e., tactile or auditory) cues and sensorimotor cues, therefore, facilitating perceptual-motor learning (Auvray & Myin, 2009). Herewith, it also resembles natural vision, which requires active sampling of visual information in the environment through eye movements in order to perceive complete objects or sceneries. Hence, the use of such technical rehabilitation devices does not equate to passively perceiving information from the environment, but actively engaging with it.

Another visual-to-auditory SSD, used for studies of localization, is the PSVA (prosthesis for substitution of vision by audition; Capelle, Trullemans, Arno, & Veraart, 1998). Unlike the vOICe, which sweeps the image from left to right to create the sonification, the PSVA provides a simultaneous sonification of the entire image and thus requires manual movement (either by the participant or the camera) to make sense of the image, similar to the concept of using eye movements to perceive a scene. Although the studies described previously that employed the vOICe implicitly required the perception of depth for the accurate localization and grasping of objects, one study with the PSVA explicitly examined the problem of depth. Both devices use a single camera, thus depth must be inferred from monocular cues rather than stereopsis. Renier et al. (2005) examined the ability of participants to locate items in depth using cues similar to those present in a natural corridor (and consequently the same cues that can create compelling corridor illusions). Although reaching and grasping were not employed, the participants were able to perceive and report depth relations between the objects in the display. Using positron emission tomography, the authors were further able to show that "visual" brain areas relevant for 3D object localization were active during the search with the PSVA, indicating that certain object features are processed in the same areas, independent of the input sense. However, the study used subjects that were blindfolded but normally sighted. When using sensory substitution devices such as the PSVA or the vOICe, individuals who have been blind from birth or in early childhood have to first learn the basics of vision that a sighted person can take for granted: size constancy, depth information, occlusion, perspective. Blind individuals also have to learn to correct for distortions in the two-dimensional image that are simply due to viewing perspective rather than revealing actual changes in the object itself (Proulx & Harder, 2008). Hence, typical vision may have been a confounding factor for the processing and performance of depth perception in Renier et al.'s (2005) subjects. In a later study, however, Renier and De Volder (2010) showed that even early blind individuals were able to make use of depth information from visual-to-auditory sensory substitution after only 135 minutes of practice. Similar findings have been reported by Segond, Weiss, Kawalec and Sampaio (2013), who used a 64-pixel visual-to-tactile SSD.

Compared to the retinal prosthesis Argus II (60 pixels; Luo & da Cruz, 2015) and even to visual-tactile SSDs like the BrainPort (144 pixels; Kaczmarek, 2011), the technical resolution for the vOICe (25,344 pixels; Striem-Amit, Guendelman, & Amedi, 2012) is much higher. Notably, technical resolution does not automatically translate into a better functional resolution—that is, a better "visual" acuity (Striem-Amit et al., 2012). The latter makes up an important aspect for ascertaining both "what" and "where" information. Using the vOICe sensory substitution system, however, congenitally blind individuals can achieve a higher visual acuity than with any other rehabilitation method (Striem-Amit et al., 2012). There appear to be two reasons for this: the capacity of the sensory system and the quality of its resolution.

Vision has the highest capacity for conveying information, even in just the phenomenological sense, well captured by the saying that a picture is worth 1,000 words. Kokjer (1987) estimated the informational capacity of the human fingertip to be in the order of 100 bits per second (bps). The eye, by comparison, has been estimated to deliver around 4,300,000 bits per second (Jacobson, 1951). The ear falls between these two limits, its capacity has been estimated at around 10,000 bps (Jacobson, 1950).

Although the auditory and visual systems are not as comparable as the tactile and visual systems (as made obvious by the analogies between the skin and the retina, and by Bach-y-Rita's decision to use tactile information for his original sensory substitution device), the ear has the potential to provide a greater amount of visual information to the brain than the skin. Moreover, even though the visual system might have the greatest information processing capacity and spatial acuity, the auditory system has the greatest temporal resolution. An experiment that assessed acuity in this domain used temporal order judgments to test the temporal acuity of the senses. In temporal order judgment tasks, two distinct stimuli (which could, for example, vary in pitch in the auditory domain or location in the tactile or visual domain) were presented consecutively, with different temporal onsets. Participants then indicated which of the two stimuli appeared first. By varying time intervals between the stimuli, temporal resolutions were assessed. The study found that while the tactile modality had a resolution of 141 ms, and the visual of 29 ms, the auditory had the highest resolution of 21.5 ms (Laasonen, Service, & Virsu, 2001). Thus, the auditory system excels at temporal processing, and a system that draws on this capacity for the translation of visuospatial information might be best placed to provide high-resolution sensory substitution. Indeed, the superior visual acuity performance found with the vOICe might be due to not only the number of pixels that can be translated by the device but also to the higher information processing capacity of hearing versus touch.

A decent level of acuity will allow one to recognize objects with some level of accuracy and, ideally, speed. Perhaps not coincidentally, most research on the recognition of natural objects with sensory substitution has focused on hearing as substituting sense. For example, Auvray et al. (2007) showed that sighted, blindfolded participants using the vOICe were able to discriminate among natural, three-dimensional objects belonging to the same category and identify object categories as well. Pollok, Schnitzler, Stoerig, Mierdorf, and Schnitzler (2005), with the same participants that were tested later by Proulx et al. (2008), found that training with three-dimensional objects at home and in the lab generalized to two-dimensional object recognition presented via images sonified with the vOICe. As intrinsic cross-modal mappings might facilitate pattern recognition and sound interpretation (Stiles & Shimojo, 2015), this might explain why using the vOICe does not require extensive training in order to reach high "visual" acuity (Haigh et al., 2013). However, training has been shown to increase the user's performance and awareness of their environment significantly (Kaiser, 2004).

Using visual-auditory SSD, Reich and Amedi (2015) showed that even concepts like visual parsing, that are critically dependent on early experience with visual information processing, can be learned without any previous visual experience (Reich & Amedi, 2015). The authors asked nine blind individuals (seven congenitally blind, one with weak light perception and one with some limited vision during her first year of life) to train their substituted vision using the vOICe. The training lasted for approximately 70 hours and was split into two main stages. In the first stage, participants learned to extract detailed 2D information from static images. In the second stage, they used the device to actively engage with the environment and learn visual real-world principles by interacting with their surroundings using, for example, hand-"eye" coordination. Following training, they were tested for visual parsing using 2D as well as 3D shapes. The stimuli and testing method was similar to that of Ostrovsky (2009), who tested three sight-restored individuals that underwent surgery between 2 weeks and 18 months prior to testing. Interestingly, the blind SSD users—who received information through a different modality—outperformed sight-restored individuals—who received this information via the natural way—on many visual tasks (Ostrovsky, Meyers, Ganesh, Mathur, & Sinha, 2009; Reich & Amedi, 2015).

A further advantage of the vOICe is that it is much cheaper than alternative devices, therefore making it accessible to a lot of people with low economic status. This is important to keep in mind, because, as we mentioned before, the majority of the world's visually impaired population lives in low-income settings (WHO, 2014).

In contrast to the recent development of SSDs for blind and visually impaired individuals, comparably little progress has been made for deaf individuals. At least in part, this is likely due to the success of restorative devices such as cochlear implants.

Especially in the late 19th century, a number of devices had been developed that tried to convey auditory information through tactile stimulation in forms of single output elements (Leder, Spitzer, Milner, Flevaris-Phillips, & Richardson, 1986), one-dimensional (Saunders, Hill, & Franklin, 1981) and two-dimensional tactile displays (Sparks, Ardell, Bourgeois, Wiedmer, & Kuhl, 1979; Sparks, Kuhl, Edmonds, & Gray, 1978; but see Kaczmarek et al., 1991 for a review). However, research in this field has decreased since the triumphal course of the cochlear implant. Currently, there is one device being developed for people with hearing loss (Novich & Eagleman, 2014) that transforms auditory information into tactile stimulation of the upper body. This device, called Versatile Extra-Sensory Transducer (VEST), currently developed under NeoSensory Inc., consists of an array of small vibration motors that are integrated into a vest, which can be worn by the user. Attached to the vest is a microphone that captures sounds from the surrounding environment, which are then translated into tactile sensations on the user's skin via the vibration motors. With this, deaf individuals will be able to perceive auditory information via vibratory stimulation on the skin of their torso.

Real-time visualization of sounds, which is well known from many applications in the music industry or musical training (Ferguson, Moere, & Cabrera, 2005), might also benefit hearing impaired or deaf individuals. However, little research has looked into the benefits of sound visualization to aid the deaf and hearing impaired in perceiving sounds in their environment (but see Ho-Ching, Mankoff, & Landay, 2003; Matthews, Fong, Ho-Ching, & Mankoff, 2006; Matthews, Fong, & Mankoff, 2005). These studies focus on the transmission of nonspeech sounds, and it remains to be investigated whether deaf individuals can gain accurate speech perception using sound visualization displays. Nevertheless, Ho-Ching et al. (2003) found their deaf participants preferred to monitor visualized auditory information in a display that used the spatial location of the sound source instead of sound frequency spectrum. This again shows that audition clearly benefits the processing of temporal information and that speech, which is distinguished by fast changes in frequency, cannot be easily substituted by the spatially dominant sense of vision.

The substitution of tactile information through audition and vision is currently the least investigated domain of sensory substitution. Impaired tactile sensation can result from injuries to single nerves or nerve groups following, for example, fractures, tumors, prolonged pressure on the nerves, diabetes mellitus, cerebral hemorrhage, chronic kidney failure, Guillain-Barré syndrome, lead poisoning, and other conditions. Diabetic neuropathy, which affects almost every second diabetic patient (Boulton, 2005), is characterized by nerve cell damage resulting in a denervation of large and small nerve fibers in the outer skin layer (Shun et al., 2004). In 2015, the international diabetes federation estimated that 415 million people worldwide suffer from diabetes (International Diabetes Federation, 2015). However, besides this very high abundance of cases of neuropathy, the substitution of tactile information through visual and auditory stimulation has not gained major attraction to investigation. Certainly, this might be due to the condition itself. Neuropathy does not affect the whole body organ (skin) but local patches of skin. This leads to a large proportion of the skin remaining functionally intact. Hence, instead of substituting a whole sense by another, it might be more applicable to replace sensory input from the local, damaged skin area to other, intact body areas. For example, in diabetic neuropathy, often the feet and legs are affected, which can in turn influence gait and balance of the individual. In order to help control their movement and prevent them from falling or tripping, sensory information from the damaged regions needs to be transferred to intact skin areas. One system that uses this principle and has been patented in 2012, is the Peripheral Sensory and Supersensory Replacement System developed by Orpyx Medical Technologies Inc. (Everett & Groenland, 2012). This system uses an array of input sensors that measure somatosensory information (e.g., pressure, force, temperature) and can be incorporated into an insole or a shoe or any other suitable device. The data is then transferred to a transmission unit that integrates and forwards the signal to the output device. The output device can be chosen, depending on the application. Electro-, vibro-, pressure-, or temperature-tactile stimulators for example allow transfer of the information to the unimpaired skin. Interestingly, because the system also allows the transformation of somatosensory data into visual data and auditory cues, depending on the output device used, the patient can gain (real-time raw as well as log) information via multiple sensory modalities. The effects of this SSD on balance and gait have been investigated in Bauman, Levangie, Nigg, Everett, & Nigg (2015). Looking at eight patients with peripheral neuropathy, they found that balance control and gait performance increased when patients were using the device, concluding that the replacement of somatosensory information is an effective method to recover the ability to conduct physical movements that play a major role in the everyday life of patients with sensory nerve damage.

Taken together, the abundance of research on sensory substitution devices in the different domains shows that there is a clear majority looking into the substitution of vision. The success of sensory restoration in the hearing impaired and the ability of the tactile domain to allow for sensory replacement result in a much smaller research output for sensory substitution in these domains.

Further Applications of Sensory Substitution Devices

Since the development of early SSDs that substitute for a lost modality, the use of such interactive technology has been extended to a wide range of applications. The idea of using SSDs to enhance sensory feedback through augmenting experiences in an intact sensory system has gained increasing popularity in recent years. Applications vary from learning to play sports or musical instruments (Großhauser & Hermann, 2009; Johnson, 2014; van der Linden, Johnson, Bird, Rogers, & Schoonderwaldt, 2011), collision avoidance in VR games (Bloomfield & Badler, 2008) or navigation (Pielot & Boll, 2010) to providing further useful information like large-scale navigational cues (Kärcher, Fenzlaff, Hartmann, Nagel, & König, 2012; Nagel, Carl, Kringe, Märtin, & König, 2005). For example, Nagel et al. developed a belt that informed the wearer about the geographical orientation—that is, where North is—using vibrotactile feedback (Nagel et al., 2005). They trained their subjects with the device for six weeks and then tested their performance on different orientation and navigation tasks. When receiving correct, geographical information through the belt, blindfolded subjects showed significantly better navigational performance compared to the belt being switched off.

In another study, van Erp, vanVeen, Jansen, and Dobbins (2005) used a vibrotactile feedback display to guide their subjects to certain waypoints along a route. Thereby, distance and direction of the next waypoint were coded in vibration rhythm and vibration location of eight adjustable tactors on the participant's upper body. Their findings were in line with that of Nagel et al. (2005), showing that participants were quickly able to make use of tactile direction information. Interestingly, increasing complexity in the vibrotactile feedback through the provision of waypoint distance information did not improve performance—indicating that usability of such devices is limited. Nevertheless, compared to their visual counterparts, such tactile navigation devices have been found to provide safe navigation tools as more attention can be paid to the environment (e.g., obstacle on the path) during walking (Pielot & Boll, 2010).

Sensory Substitution and the Brain

By far, one of the greatest advantages of sensory substitution is that it allows individuals to access information from one sensory modality that is not accessible (at least not to the same extent) in another modality. Here, SSDs can help us gain valuable insights into the neural processing of sensory information.

For a long time, the assumption that information from different sensory modalities are processed in sensory-specific brain areas, before getting integrated in higher associative areas, has been widely accepted (Felleman & Van Essen, 1991; Jones & Powell, 1970). However, this traditional view has been challenged by studies reporting non-visual information processing in presumptive visual areas in blind participants (Cohen et al., 1997; Ptito, Moesgaard, Gjedde, & Kupers, 2005; Struiksma et al., 2011; Uhl et al., 1991; Vanlierde et al., 2003). Indeed, there is a growing body of evidence about the generation of cross-modal responses in primary sensory areas (Calvert et al., 1999; Calvert, 1997; Foxe et al., 2002; Fu et al., 2003; Kayser, Petkov, & Logothetis, 2008; Kayser, Logothetis, & Logothetis, 2007), arguing for a reevaluation of the classical, modality-dependent model of brain organization. Using SSDs, many studies were able to demonstrate that during substituted "seeing" the same neural networks that are recruited during normal vision are activated in sighted and blind SSD users (see Arno et al., 2001; Ptito et al., 2005; Reich, Maidenbaum, & Amedi, 2012; Ricciardi et al., 2014 for reviews). These activations seem to occur independently of the user's level of training with the device (Arno et al., 2001) and are stronger in congenitally blind individuals than in blindfolded sighted individuals (Ptito et al., 2005).

One example that shows how sensory processing is defined by the metamodal organization of the brain is the extraction of shape information from auditory soundscapes. Shape is a fundamental cue in determining the nature of an object and is usually assessed via visual or haptic exploration, whereas audition can only provide little information. Work with the vOICe showed that the processing of auditory shape information from soundscapes activated areas in the lateral occipital complex that are otherwise mainly involved in visual and tactile shape processing (Amedi et al., 2007; Amedi, Jacobson, Hendler, Malach, & Zohary, 2002; Amedi, Malach, Hendler, Peled, & Zohary, 2001). The extraction of spatial information from auditory cues in this case is not only limited to the auditory pathway but extends to areas in the brain that usually process visual input. This shows evidence for a computation-based brain organization (James, Stevenson, Kim, Vanderklok, & James, 2011; Pascual-Leone & Hamilton, 2001; Proulx, Brown, et al., 2014)—that is, cortical areas (e.g., occipital regions) exhibiting certain computations (e.g., spatial discrimination), irrespective of the inputted sensory modality.

Further support to the idea that the brain has a metamodal organization comes from studies investigating the generalization level of perceptual learning using visual-auditory and tactile-auditory SSDs (Kim & Zatorre, 2008; Kim & Zatorre, 2010). Here, the authors demonstrated that abstract shapes, which were learned through hearing, were generalized to other modalities. They trained blindfolded, sighted participants to recognize these shapes by listening to their respective soundscape. Soundscapes were created using an image-to-sound conversion algorithm adopted from Meijer (1992, but see Figure 15.8). Following training, participants were not only able to match the pairs of visual/tactile shapes with the right soundscapes but even showed generalization to novel auditory-visual and auditory-tactile pairings. What's more, in one of the studies (Kim & Zatorre, 2010) the authors found that participants who have only been trained to match auditory-tactile shape pairings were able to transfer this substitution learning to untrained visual stimuli. Taken together, these findings support the hypothesis that our brain is not only organized as a set of different sensory areas but by computation/function (James et al., 2011; Pascual-Leone & Hamilton, 2001; Proulx, Brown, et al., 2014). Certainly, some low-level areas show a preference for the processing of information from one specific sensory modality, but it is becoming more and more evident that these areas are not purely compelled to these modalities but rather to the stimulus feature they process.

Age of Onset for Rehabilitation Procedures

In 1965, Wiesel and Hubel tested the effects of timing of visual deprivation on sight restoration in kittens. They lid-sutured either one eye or both eyes for the first 3 months and then reopened them. After 3 to 18 months, they looked at changes in anatomy and physiology of the visual system and found that visual deprivation in the first 3 months of life led to long-lasting changes in the visual pathway, even after a late prolonged period of visual experience (Wiesel & Hubel, 1965). Even after 5 years of visual experience following deprivation, recovery was very limited; however, this depended largely on the time of onset of visual deprivation (Hubel & Wiesel, 1970). This led them to conclude that when a lack of sensory input persists beyond a certain time period in life, neural reorganization will impede the functional restoration of vision with a similar to normal pattern of ocular representation.

These early studies of Hubel and Wiesel inspired a great number of researchers to look into the effects of impairment onset on the outcome of sensory rehabilitation. A great number of studies describe differences in information processing between early and late blind individuals (e.g., Burton et al., 2002; Cohen et al., 1999; Collignon et al., 2013; Fine, 2008; Sadato, Okada, Honda, & Yonekura, 2002; Voss, Gougoux, Zatorre, Lassonde, & Lepore, 2008). Many of these reported on the recruitment of neural matter in visual cortex regions for auditory (Bedny, Konkle, Pelphrey, Saxe, & Pascual-Leone, 2010; Collignon et al., 2013, 2015; Voss et al., 2008) and tactile (Burton et al., 2002; Cohen et al., 1999; Sadato et al., 2002) processing (see Figure 15.9).

However, how visual deprivation and cross-modal reorganization affect the functional, behavioral outcome in late blind (compared to early blind) individuals is not clearly established (for a review see Voss, 2013). That is, even if both groups show differences in neural activation patterns, the behavioral outcome might be similar. Indeed, some studies find that behavioral performance is similar for early and late blind individuals and that they are even comparable to sighted individuals on spatial auditory tasks (Cappagli & Gori, 2016; Voss et al., 2004). In spatially irrelevant auditory tasks (e.g., pitch discrimination) on the other hand, early and congenitally blind individuals performed better compared to late blind (Gougoux et al., 2004) even when controlled for musical experience (Wan, Wood, Reutens, & Wilson, 2010). At the same time, it remains questionable if, even when sensory restoration in the late blind is successful, the individual really gains functional or behavioral benefits (Garcia et al., 2015). A recent study demonstrated a delay in the development of spatial auditory precision (Cappagli & Gori, 2016). The authors showed that blind and visually impaired adults, but not children, performed just as well as sighted individuals on an auditory localization task. This might point to the importance of much slower developing perceptual processes like multisensory integration (Gori et al., 2008; Petrini et al., 2014), especially in the unimpaired senses. That is, if children develop the ability to integrate information from the remaining, intact senses at a later age, the resulting increase in information reliability allows for compensation of a disrupted auditory representation of space. It has already been shown that the

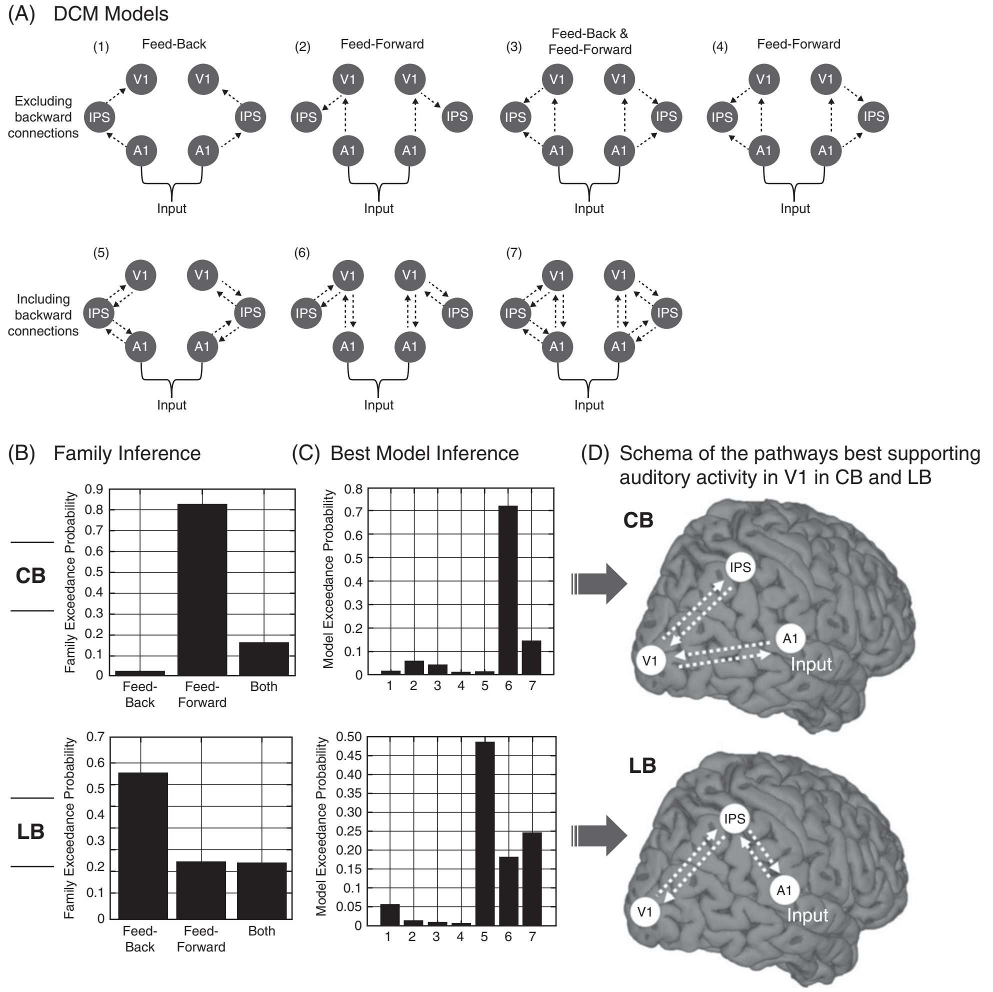


Figure 15.9 Schematic representation of the differences between congenitally blind (CB) and late-onset blind (LB) individuals in how auditory information flows from A1 toward V1 via the intra-parietal sulcus (IPS). This pathway is based on findings of Collignon et al. using dynamic causal modeling analyses.
Source: From Collignon et al. (2013). Reprinted with permission.

integration of audio-visual information is disrupted in individuals that were visually deprived for the first 2 years of life due to cataracts but regained sight following surgery (Guerreiro et al., 2015). Furthermore, there is evidence that auditory-tactile interactions are affected by visual deprivation via different spatial attention mechanisms (Hötting, Rösler, & Röder, 2004). This emphasizes the importance for future research to look into the effects of multisensory integration during development for the construction of a precise representation of the environment and, ultimately, optimal behavior. Understanding these processes will enable us to determine which rehabilitative methods will work best at different points in time. Furthermore, this reinforces the clear need to investigate if there are critical ages during which sensory substitution training will be most successful to rehabilitate sensory deficits.

Current Advancements and Future Outlook in Rehabilitation Technology

As we have discussed so far, sensory substitution devices as well as restorative technologies provide an elegant solution to increase our understanding of brain plasticity, brain organization, as well as the development of perception and action. These technologies enable us to learn about the ways in which the human brain processes information from different sensory inputs, how it copes with sensory deprivation, and how cross-modal reorganization affects the outcomes of different types of sensory rehabilitation.

Visual restoration techniques like retinal and cochlear prostheses or embryonic stem cell treatment might hold great promises; however, at the moment their applicability is largely constrained by the complexity and risks of invasive treatment, long and arduous rehabilitation processes, as well as their cost and the rather low visual resolution they are able to achieve. These treatments are thus accessible to only a subgroup of visually impaired people who live in higher income settings and do not guarantee full visual rehabilitation. Cochlear implants, on the other hand, have a more successful outcome in sensory restoration, and recent studies investigating the long-term effects of implantation found that the majority of children receiving a cochlear implant significantly progressed in speech perception and production and continued to use their devices even 10 to 14 years following the implantation (Beadle et al., 2005). This indicates long-ranging communication benefits for deaf children who have been provided with cochlear implants. However, one must consider that the outcome of the cochlear device greatly depends on the age this device is implanted as well as on the onset of deafness. Individual differences in brain organization and speech processing (Lazard et al., 2010) can have further impact on the success of auditory rehabilitation.

Considering the trade-offs between effort (potential risks during surgery, financial costs, healing, and training duration) and outcome (visual acuity, functional vision, increase in interactive potential as well as independence and confidence), it is evident that sensory substitution devices offer a cheaper and less-invasive alternative for rehabilitation compared to current sensory restoration methods. However, the distribution and acceptance of these devices encounter other hurdles. Besides their promising potential, the application of SSDs so far has not widely spread beyond controlled research settings (Maidenbaum et al., 2014). The progress in making these devices cheaper and less restricted to certain hardware by, for example, allowing them to work on common devices like smartphones, as well as developing successful training programs, will hopefully facilitate the adoption of SSDs to everyday settings. Interactive training (Reynolds, Glenney, & College, 2012), for example, that not only takes perception but also action into account, should be incorporated into the process of SSD application for everyday tasks in the real world. The skepticism and reluctance, especially in older adults (Brickfield, 1984; Kim, 2012) to try new or advanced technological devices might arguably be another factor that contributes to the slow progress in adoption of such devices and rehabilitation methods. This, however, is an issue that should have less of an impact on the next generations.

The current functional limitations of these devices arise from multiple domains: (a) technological, such as the limited resolution of the device; (b) modality, such as the resolution or nature of the sensory system substituting for vision; (c) mapping algorithm (i.e., how sensory information from one sense is translated into information in the other sense), based on similarities in feature processing across senses; and (d) learning and plasticity, such as the required optimal training to achieve a long-lasting multisensory perceptual learning (Proulx, Brown, et al., 2014) and a good level of generalization (Brown & Proulx, 2013). There are certainly reasons to be optimistic for the future of sensory substitution. First, naïve users are able to perform not only above chance on spatial tasks with minimal training but even to near ceiling degrees of visual acuity; moreover, even a little bit of training improves performance (Haigh et al., 2013), and that improvement can be maintained over several months and be generalized beyond that specifically practiced during training (Brown & Proulx, 2013). These points are crucial and should be considered in the context of the development of normal vision; certainly human infants do not learn to see as adults in merely one day. The current state of the art also suggests that different devices and modalities might be advantageous for different tasks, though it is unclear at the present time whether this is due to the nature of the devices or the substituting modalities. With the help of computer science-based knowledge about the limits and possibilities of interactive technology, this would enhance the potential of successful rehabilitation techniques for people with sensory deficits.

CONCLUSIONS AND FUTURE OUTLOOK FOR SENSORY REHABILITATION

Due to the complexity of our environment and our physical limitations, perception does not reflect reality but aims to create a representation of our world that is as veridical as possible. To support this process, our central nervous system combines redundant information from several senses. Internal as well as external random noise has to be accounted for and determines the reliability of the different sensory modalities. Thereby, certain senses are better adapted to provide information for certain stimulus features than others. Due to its high spatial resolution and system specific features, vision plays a dominant role in spatial tasks, whereas audition grants the highest temporal resolution, giving rise to a metamodal (Proulx, Brown, et al., 2014) or supramodal (Ricciardi et al., 2014) organization of the brain. Several recent studies suggest that during development the senses calibrate each other, with the most robust sense for one task teaching the less robust one. At the same time, research on sensory impaired individuals shows evidence for sensory compensation, whereby the remaining senses show supra-normal performance in order to compensate for the lack of sensory input from the impaired modality. Statistically optimal integration of multisensory information does not emerge before late childhood, around the age of 10–12 years. Children that are deprived of sensory input early in life often show modality-specific impairment in the perception of their environment (e.g., poor spatial representation in the blind).

In this chapter, we have focused on perceptual processes with focus on the sensory impaired and what interactive technologies are currently used to promote independence through rehabilitation. We have highlighted that, over the last few decades, a lot of progress has been made in the development and application of technologies that facilitate autonomy and independence in people with visual, auditory, and motor impairments. From this, we concluded that the most successful method for hearing impairment up to now has been found in sensory restoration techniques (i.e., cochlear implants). The field of neurotechnology and neural interface systems is relatively young but already shows promising progress with the development of devices like the BrainGate or sensory-motor hand prostheses. Visual rehabilitation, on the other hand, does not seem to have found an ideal solution to replace or restore vision to a satisfactory extent. Importantly, as the majority of people with visual impairments reside in developing countries and might have less chances of getting expensive surgery, it is crucial to make alternative technology affordable to ensure its being accessible to everyone who needs it. However, increasing research in the field of sensory substitution and sensory restoration clearly is encouraging, and we look forward to advances in the design and application of affordable, interactive technologies with the aim to provide independence and confidence to those who have visual deficits and must deal with a world built by the sighted, for the sighted, without enough thought of inclusivity or accessibility. Research on sensory substitution and restoration further enhances our understanding of associated perceptual and multisensory processes and the brain as a plastic task-machine. Although, for many years, our understanding of the sensory brain has been characterized by distinct, modular information processing domains, we are now accepting that a better representation of the brain requires what is now known as a metamodal or supramodal organization.

To this end, we need to achieve a better understanding of the biological and psychological mechanisms underlying multisensory perception and neural reorganization following sensory loss in order to understand under which conditions sensory impaired individuals really gain from using certain rehabilitative technologies. This will make answering the following questions a vital part of future research:

- How does sensory impairment or loss influence the development of multisensory integration and, more specifically, multisensory integration of the unaffected senses?
- Which sensory rehabilitation techniques predict the best functional outcome for populations of a certain age and degree of neural reorganization?
- How can interactive sensory rehabilitation technologies like prostheses or sensory substitution devices be optimized and taken from a research-based setting to the wider, more general public?
- Is neural reorganization and plasticity due to sensory impairment and loss confined to primary sensory areas or extend to higher, multisensory areas (e.g., posterior superior temporal sulcus/gyrus, inferior frontal gyrus)?
- What are successful techniques, similar to cochlear implants for the hearing impaired, for treating visual or motor deficits?
- How can we create a multi-modal device that incorporates the best of the currently available devices (for example, combining an auditory device for high-resolution object recognition and a tactile device for navigation)?

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