Chapter 8
Sensory Substitution Through Vibrotactile Stimulation

Árni Kristjánsson, Ivan Makarov, Nashmin Yeganeh, and Runar Unnthorsson

8.1 Introduction

Picture yourself standing in a river in northern Iceland, fishing on a sunny day. You feel the power of the current of the river through your waders that are keeping you dry (a haptic sensation), you hear the ducks who have their nests along the riverbank, the river flowing, and the sheep calling their newborn lamb as they graze close by (audition). While you watch the river flow and keep an eye on the lure (vision), you sense the aroma of the berry bushes on the riverbank that you try to not stray too far away from and the fresh water flowing down from the highlands (olfaction). Haptic feedback from the riverbed and from the river current then provides essential proprioceptive input allowing you to maintain balance. This scene clearly conveys how our representation of the perceptual world is made up of visual, auditory, haptic, olfactory, and proprioceptive information. Our representation of the perceptual world is, in other words, *multimodal*.

Our largest sensory organ is the brain and a commonly accepted notion is that the brain constructs mental models of the world from prediction about the world and from sensory input [1–3]. The importance of this *creative role* of the brain and the

---

Á. Kristjánsson (✉)
Faculty of Psychology, School of Health Sciences, University of Iceland, Reykjavik, Iceland
e-mail: ak@hi.is

I. Makarov
Faculty of Psychology, School of Health Sciences, University of Iceland, Reykjavik, Iceland

Faculty of Industrial Engineering, Mechanical Engineering and Computer Science, University of Iceland, Reykjavik, Iceland

N. Yeganeh · R. Unnthorsson
Faculty of Industrial Engineering, Mechanical Engineering and Computer Science, University of Iceland, Reykjavik, Iceland

E. Pissaloux, R. Velazquez (eds.), *Mobility of Visually Impaired People*, Signals and Communication Technology, https://doi.org/10.1007/978-3-031-91550-5_8

multimodal input that informs this construction has been known throughout human intellectual history. In Aristotle's book on Psychology, *De Anima,* he discusses what he called the common sensible (*koine aesthetes*), which involves a unified perception of the world that is typically informed by all the senses. Ibn Al-Haytham emphasized this creative role of the brain in his seminal *Book of Optics* [4]. Bishop George Berkeley, in his theory of perception [5], emphasized that sensations that overlap in time become associated with one another and also that such associations become stronger as they are repeated, again emphasizing how our concept of the perceptual world is multimodal, combining information from all the senses. In the seventeenth century, William Molyneux asked the philosopher John Locke [6] whether a blind man who suddenly gained the ability to see would be able to recognize objects that he had previously only interacted with through touch with his restored vision (see discussion in [7]), which is a fundamental question in the context of sensory substitution. While Locke's answer to Molyneux's question was a decisive "no," the multimodal nature of our perceptual representations suggests that humans and other animals are much better at this than Locke assumed [8, 9] while there are still considerable deficits [10]. Charles Darwin [11] argued that "When we direct our attention to any one sense, its acuteness is increased; and the continued habit of close attention, as with blind people to that of hearing, and with the blind and deaf to that of touch, appears to improve the sense in question permanently."

All these examples clearly indicate how researchers throughout intellectual history have considered our representation of the perceptual world as a multimodal intellectual construction.

It is important to emphasize that this representation that the brain constructs, is by no means thought of as a precise representation of the world—instead, it is a *useful* one [12] perhaps analogously to how an operating system, such as the one in our computers, is a useful interface for working with the electronics underlying its performance [13] while the tokens denoting files and the windows and folders that we use to organize the information bear no resemblance to the underlying electronics. Instead, our representation of the world reflects how evolution has equipped us with the tools that we need for successful interaction with the world.

Overview of chapter. In the following, we will describe our work on providing sensory feedback to people with sensory impairments by conveying information through another intact sense. We emphasize that for such sensory substitution the operating principles of the perceptual channels involved need to be thoroughly understood. In particular, we will focus on our work on the properties of haptic perception.

8.2 Sensory Impairment and Sensory Substitution

What happens when information from one of these perceptual channels is missing? For a person born without a functional visual system, the representation of the world is undoubtedly quite different than for those with normal eyesight.

In recent years, investigators have increasingly tried to address the question of whether this loss can be compensated for in any way, for example, by providing information from the missing sense through another one. The quick answer to this question is a clear “yes.” There is good evidence that information that is not available through a sense that is deficient can be substituted by presenting the same information through another sense (see [14–16]). Similarly, the brain regions that are continuously in use throughout the lifespan may stay well-tuned to the tasks that they are involved in, which is, in fact, a relatively under-explored research avenue.

Such *sensory substitution* is not a new idea—a good example is how the white cane has, in one form or another, been around for millennia [17], allowing visually impaired people to navigate their environments. Information about obstacles is conveyed from the cane to their hands through pressure and vibration. With increased technological advances, possibilities for much more sophisticated replacement devices have emerged.

The consensus has in recent decades been that the brain is modular, with specific brain areas subserving different functions [18–20]. Various brain sites or networks, each devoted to particular functions or to analyzing particular information have been identified. While this is not incorrect, as such, recent evidence shows that the potential for reorganization of the brain is vast. An important consideration in this respect is that the brain is capable of considerable reorganization in cases where one sense becomes deficient. It can even reorganize so that parts of the brain devoted to a sense that is compromised can be taken over by another sense. The most important constraint for such reorganization may be at what time the reorganization occurs. There may be *critical periods*, during which they can be taken over by other functions more easily and straightforwardly than later with more settled functional organization. Evidence from studies of visual deprivation of monkeys shows how the brain can reorganize, altering the modality that elicits neuronal responses in areas that are responsible for handling visual information in monkeys with functioning eyesight [21]. Other deprivation studies (on kittens) show how active self-generated interaction with the visual world is necessary for normal visuomotor behavior [22]. There is also evidence of auditory localization activity occurring in the visual cortex in the blind [23–25]. The primary visual cortex is indeed likely well suited to such localization because of how it is organized by the locus of retinal input in sighted observers.

A well-documented example is how Braille reading with the fingers can recruit areas devoted to visual perception in people with intact vision ([26, 27]). There is also evidence that vision can recruit auditory areas following hearing loss [28].

Areas that have been thought to be concerned with higher level aspects of vision such as word, or sentence processing and face processing, show responses to haptic or auditory input in visually impaired people. Reich et al. [29] showed how a region called the visual word form area in the fusiform gyrus is activated during Braille reading. Saccone et al. [30] recently showed how the visual networks of blind people can even be sensitive to higher level cognitive aspects such as sentence grammar. Kim et al. [31] found that in blind individuals the region corresponding to the so-called visual word form area (VWFA) in the ventral stream responds to words written in Braille and shows modulation of activity by sentence complexity. Ortiz et al. [32] reported that the activity induced by touch in visual cortex could lead to sensations similar to phosphenes in the blind, who reported seeing flashes of light following tactile stimulation. Goayal et al. [33] reported that activations in face-sensitive areas in the fusiform gyrus (typically considered to involve *visual* analysis of faces) can occur from tactile face recognition and Ratan Murty et al. [34] reported face selectivity in the lateral fusiform gyrus as congenitally blind participants touched 3D-printed faces with their fingers. Kanjilia et al. [35] found visual cortex activation in a go/no-go task in the congenitally blind. Abboud and Cohen [36] demonstrated interactions between cognitive networks and what typically is the visual cortex in the seeing, in people who became blind at an early age. Similar conclusions have been reached by Bola et al. [37], Mattioni et al. [38], Mattiono et al. [39], and Raczy et al. [40]. Another example comes from Van Erp et al. [41] who conveyed the direction of a stimulus with vibration location and distance with frequency (see also [42, 43]).

All this highlights a crucial point. Even if people lose vision (for example), through damage to their eyes or their optic nerve there is still a lot of neural hardware that has evolved for the purpose of organizing input from the eyes. So, even without functioning eyesight, we do not necessarily lose the ability to see [44]. We still possess intact neural mechanisms that can process such information. This point was made centuries ago by Rene Descartes [45] in his analogy of a blind man determining distance with two sticks, just as those with intact vision can use binocular disparity to determine distance. In the end, the “language” of the brain is electric and chemical signaling, irrespective of whether the input is photons for vision, air pressure for audition, or physical contact to the skin. The human nervous systems has repeatedly been shown to have quite impressive flexibility following damage [26, 46, 47] and the current question revolves around the degree to which this information can be utilized.

8.3 The Sound of Vision Project

Our research group has, for a decade now, investigated sensory substitution. Our initial investigations were part of the *Sound of Vision* project (SOV; see [48–52]) which was aimed at providing the visually impaired with a multimodal representation of the surrounding world where information from head-mounted cameras was translated into custom-made auditory and haptic languages.

To generate the audio encoding, head position was continuously measured with a head-mounted inertial tracker. Visual images from the head-mounted cameras were translated into auditory information with the so-called fluid flow sound model. The model relies on continuous depth information from the head-mounted cameras and is designed to encode constantly changing scenarios. A model that was based on bubble sound statistics was used to generate liquid sounds that each convey different aspects of the surrounding environment. For example, depth information within a given image region is mapped into aspects of a bubble sound, while the direction of a particular stimulus (or location) is mapped into the relevant spatial sound features. Different bubble sounds then denote different levels of obstacles close to the user, the larger the number of bubbles sounding, and the sound becomes louder, the closer the potential obstacles are.

But in the interest of utilizing our multimodal brain representation of the environment, we also developed a haptic language, where information from the head-mounted cameras was conveyed by a 6 by 10 array of tactile actuators applied to the lower back of the users. The haptic encoding was based on the users' body position relative to the position of their head, so the haptic representation of the location of stationary objects was kept constant when users rotated their head but did not move the rest of their bodies. Information from the IMU was again used as input for this. For example, the direction of the surface nearest to the user within a 3.5-m radius was represented with the vibration of the tactor on the tactile array that indicated that direction. Frequency and amplitude of the activated motor were then inversely proportional to the distance of the object, where the frequency and amplitude increased the closer the object was to the user. An additional feature of the haptic language was that the motor representing the closest cell in the depth map was augmented with activations from neighboring motors to amplify the vibrotactile information, resulting in a 2 by 2 array of activated tactors.

8.4 Haptic Stimulation as Sensory Substitution

Just like the other senses, the tactile sense involves building a representation of the world. Unfortunately, there is much less understanding of the processing characteristics of this channel than of the visual or auditory world construction in humans. In parallel with the development of the SOV sensory substitution device, our research group has therefore carried out extensive experimental investigations of perception of vibrotactile stimulation to develop knowledge of the psychophysical properties of haptic perception. Our aim has been threefold: (i) to help people with hearing impairments navigate their environment by providing information about their environment, (ii) to develop ways to augment the enjoyment of music by users of cochlear implants, and (iii) to create a general haptic stimulation device for use within low-visibility environments that could be used to help people navigate in low-visibility environments, and for people with visual impairments.

8.5 Haptic Perception

When devices conveying tactile information are developed, it is important to consider the properties of the so-called mechanoreceptors that play a key role in the perception of mechanical stimuli such as pressure, touch, vibration, and stretch of the skin. These receptors are found throughout the body while their dispersion varies by body region. Each mechanoreceptor type possesses unique traits and functions, enabling the body to perceive and differentiate diverse mechanical stimuli in its surroundings. Together, these receptors contribute to the intricate sensory perception of touch and perform vital functions in tactile sensation, proprioception, and also detect mechanical occurrences within the body, such as joint movement (see Fig. 8.1).

The *Merkel Discs* are found in the basal layer of the outermost layer of the skin (the so-called epidermis), particularly in the fingertips and lips, in other words body parts that have high tactile sensitivity. They perceive pressure and are crucial for the perception of texture and fine tactile details.

Meissner's corpuscles are mostly located in the papillae (the thin top layer of the skin) of the dermis on hairless skin: fingertips, palms, lips, and the soles of the feet. They are responsible for light touch and low-frequency vibrations, enabling the detection of tactile stimuli with high sensitivity and precision.

The *Pacinian Corpuscles* are located in the dermis (the inner layer of the skin) and the hypodermis (the bottom layer furthest from the skin surface) and in joint capsules and other connective tissue. These mechanoreceptors are responsible for detecting deep pressure and high-frequency vibrations and for proprioception.

Finally, the *Ruffini Endings* (or Ruffini Corpuscles) are located in the dermis and hypodermis and at the joints. Ruffini Endings are receptors that slowly adapt to skin stretching and sustained pressure providing information about skin deformation and joint position.

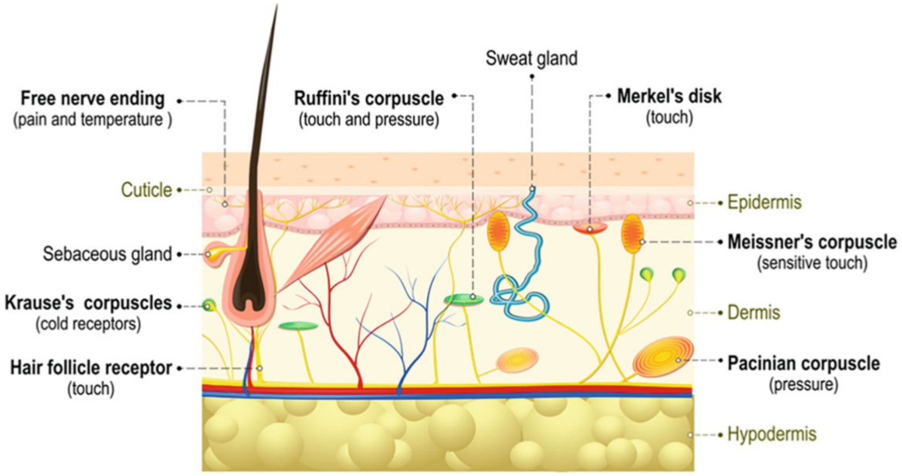

Fig. 8.1 The mechanoreceptors in the skin (see text for further details)

Our research group has conducted studies of tactile attention and tactile perception for about a decade. One goal has been to assess thresholds for vibrotactile discrimination for different tactor types and body parts. The results have, not only, cast new light on vibrotactile sensitivity, but our hope is that this information will, furthermore, be of use in the design of devices that convey information through vibrotactile stimulation, in particular devices aimed at sensory substitution. These results have highlighted the crucial roles played by inter-tactor spacing, choice of tactor type, and direction of stimulus presentation for vibrotactile spatial acuity. Overall, this set of findings can contribute to the formulation of guidelines for the design of tactile displays. In addition, we have studied tactile illusions. This research has also revealed that the mechanoreceptors in the skin appear to be more sensitive to vibrations than to pressure [49–51].

8.6 Summary of Findings from Investigations of the Processing of Vibrotactile Stimulation

In Jóhannesson et al. [53], we tested vibrotactile discrimination on the lower back. Observers judged whether the second vibration of two successive ones was to the left, right, or in the same location as the first. While accuracy decreased with smaller distance between the tactors, discrimination accuracy was still well above chance for the smallest possible distance (13 mm center-to-center) for these eccentric rotating mass (ERM) tactors. This means that the distance threshold for vibrotactile stimulation is below 13 mm, far lower than some previous estimates [54, 55].

Notably, in Hoffmann et al. [49–51] we then investigated what effect the characteristics of tactile actuators, such as frequency, or acceleration in addition to where the stimulation was applied, is on measurements of spatial acuity. All of these factors greatly affected spatial acuity for vibrotactile measurements, highlighting the crucial role of the stimulation type for vibrotactile acuity. In Hoffmann et al. [49–51], we also observed an anisotropy in how vibrotactile stimuli are perceived, where spatial acuity was higher for horizontal than vertical presentation. This may be related to differences in the so-called intensity order illusion as a function of the direction of stimulation ([56], see discussion below).

Another important finding was the investigation of the optimal frequency values for vibrotactile stimulation [57]. Participants wore a wristband with L5 actuators on their inner and outer wrists. Ævarsson et al. [57] found the highest sensitivity for 200 Hz stimulation for the inner part of the wrist (optimal range between 100 and 275 Hz). For the outer wrist, the optimal frequency was 125 Hz (optimal range between 75 and 200 Hz). It is well known that hairy parts of the skin tend to be more sensitive than glabrous skin [58] and the results of Ævarsson et al. [57] indicate small but notable differences in optimal frequency for stimulation of the two skin types. These results provide us with basic parameters for stimulation that can be

Fig. 8.2 (**a**) The apparatus used in Yeganeh et al. [59, 60]. The figure shows sleeves of stretchable material of five different sizes with different distances between actuators. (**b**) The experimental setup in Yeganeh et al. [59, 60]

used in other studies of vibrotactile perception on the skin and for future sensory substitution devices.

An example of the application of these results is how we use values from these sensitivity ranges to find the optimal distance between actuators using five different sleeves made of elastic material with vibrotactile stimulators that participants wore on their forearm ([59]; Fig. 8.2). The sleeves had different distances between actuators (as close as possible, 5 mm, 10 mm, 15 mm, 20 mm). All sleeves had three actuators on stretchable fabric that enabled adjustment by different sizes of people's forearms. We also compared vibrotactile acuity on the inner (glabrous skin) and outer (hairy skin) parts of the forearm. Accuracy was highest when the tactile stimulators were placed with a 2 cm distance between them, but there was little or no accuracy difference between the inner and outer forearm. Note, however, that this may partly reflect that the task was too easy, and that with increased task difficulty, larger differences could be seen (e.g., [57]).

Subsequently, we performed another study to assess where on the human forearm resolution is the highest [60]. Participants were stimulated with two sequential vibrations using the sleeve with the best performance from Yeganeh et al. [59]. Participants judged whether a second vibration was in the same location, closer to the wrist or to the elbow, than the preceding vibration. Another important independent variable was the frequency of the stimulations (100 Hz, 150 Hz, 200 Hz, 250 Hz). These frequencies were chosen based on previous our results on vibrotactile sensitivity as a function of frequency [57]. The most sensitive regions for the perception of tactile information were in close proximity to the wrists and to the elbows, while accuracy was lower for stimulation between them, indicating that less information can be conveyed in this region than closer to the joints. Interestingly, accuracy did not vary much by frequency. This may reflect that the whole frequency range that we used was within the range of best performance for vibrotactile stimulation for both the upper and lower wrist [57]. Overall, these

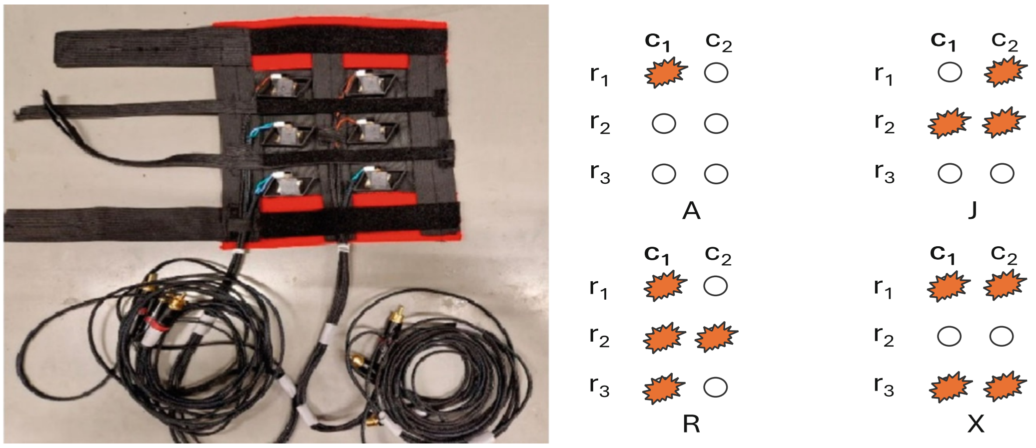

Fig. 8.3 The left panel shows the tactile actuators used in Yeganeh et al. [61] to present Braille letters to the forearm, mounted on the stretchable, wearable material. The right panel shows four vibration patterns, denoting the letters A, J, R, and X from the Braille alphabet

results provide insights about the best stimulation locations for potential sensory substitution devices on the forearm.

In Yeganeh et al. [61], we compared sequential and simultaneous presentation of tactile information. We created a vibrotactile sleeve of stretchable material (similar to [59, 60]) with six vibrotactile stimulators in a 2 by 3 array (see Fig. 8.3). Our aim was to send vibrotactile signals denoting letters from the Braille alphabet. We also compared long and short patterns (2 and 3 vibrations versus 4 and 5 vibrations to convey the pattern). Participants had to recreate the presented patterns of stimulation. Let's say that the aim is to convey letter R in Braille. In the 2 by 3 array of tactors (see Fig. 8.3), this would be conveyed by activating all three tactors in column 1 (the left column) and the middle tactor in column two (the right column). We then either presented all of these four tactors simultaneously, or sequentially (one after the other). The results showed that observers found it harder to recreate the patterns when they were presented simultaneously than sequentially. On the one hand, this difference between simultaneous and sequential presentation is not surprising, but it is an important piece of information for the effective conveyance of information since it suggests limits on what can be presented. Another informative finding was that participants were significantly less accurate at recreating long patterns. We should therefore seek alternative ways of presenting complicated information that requires long combinations of stimulation.

8.7 Tactile Illusions

Tactile illusions can provide important insights about tactile perception and attention. Illusions involve the misperception of the actual stimulation applied to the senses and reveal the predictions of the brain about the perceptual world and are a rich source of information about many basic operational principles of perceptual systems (Fig. 8.4). Our group recently discovered the *intensity order illusion* [49–51, 56, 62]. The illusion occurs when two stimulations are applied in succession (with a brief interstimulus period) at the same location on the back, but observers are asked to indicate whether the second stimulation was above or below the first one. If the second stimulation is of higher intensity (through a combination of amplitude and frequency) than the first one, the direction is misreported as up, while the converse is the case if the second stimulation is of lower intensity (the second reported as below the first; see Fig. 8.4c).

Another illustrative tactile illusion is the so-called sensory saltation, also referred to as the cutaneous rabbit ([63, 64]; see Fig. 8.4b). This phenomenon entails rapid, repeated stimulation at adjacent locations on the skin. For instance, a sequence of three taps applied to two skin sites can elicit the sensation of an object (the "rabbit") hopping along the skin, resulting in an illusory perception of stimulation occurring between the two actual stimulated locations. Relatedly, the funneling illusion [65, 66] involves the perception of two adjacent simultaneous vibratory stimuli as originating from the space between the actual stimulations. These illusions underscore the extensive spatiotemporal interactions involved in processing tactile stimulation, whether they reflect modulations in the activity of the somatosensory cortex or higher order interpretative brain processing.

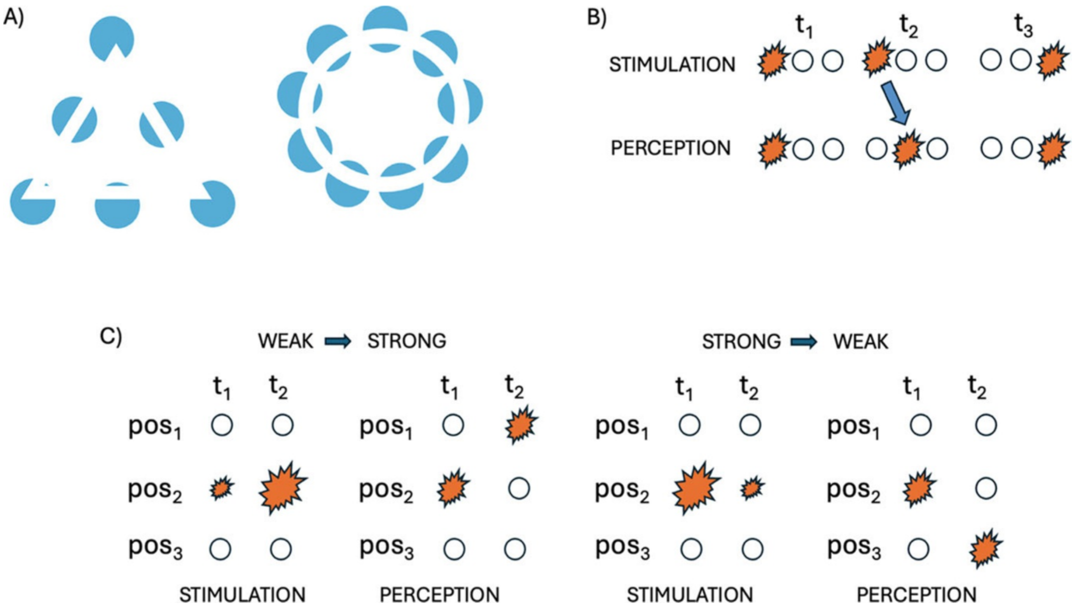

Fig. 8.4 Visual and tactile illusions. (**a**) Kanizsa style visual illusions. Neither the triangle on the left nor the ring on the right is actually there, the two shapes are simply implied by the cyan-colored inducers. (**b**) Sensory saltation (aka the cutaneous rabbit illusion) where the second stimulation (of three) at t_2 (a few hundred milliseconds after t_1) is misperceived as occurring at the middle location. (**c**) The intensity order illusion, where a second vibration is perceived as occurring above the first one if it is of higher intensity and as occurring below the first one, if it is of lower intensity, even though the two stimulations are actually in the same location [56, 62]

Moreover, well-known illusions observed in different sensory modalities, such as vision, also occur in tactile perception. The Delboeuf illusion and the vertical-horizontal illusion are two examples. Other visual illusions, including the Bourdon [674], Müller-Lyer [68], and the Ebbinghaus illusion [69]), have tactile counterparts. Additionally, illusions associated with underestimation of distance between stimuli and overestimation of time have been observed in the tactile modality. These include the tau effect [70], the kappa effect [71], and the apparent haptic movement illusion [72], which may be related to the cutaneous rabbit illusion discussed earlier.

Illusions generally involve nonveridical perception of the presented stimuli and demonstrate the large role played by the interpretative processes of the brain in tactile perception. Perotta et al. [73] have recently shown how participants can use their skin to interpret auditory stimuli. They presented information through a custom-made wristband and trained deaf and hard-of-hearing participants to identify sounds that were translated into spatiotemporal vibration applied to observer's wrists. Using a three-alternative forced choice task, Perotta et al. [73] found that participants could determine the identity up to 95% and on average 70% of the stimuli simply by the spatial pattern of vibrations, and performance significantly improved over the course of 1 month showing the importance of practice for sensory substitution, consistent with results on the *Sound of Vision* device in Hoffmann et al. ([49–51]; see also [14]).

8.8 Where to Stimulate

While the skin has great potential for conveying a lot of information, a key prerequisite is that there has to be neural hardware that can process the conveyed information. The information must also be useful and informative about the environment, and our perceptual systems must be able to process the information in a way that is *useful* in interacting with environment.

Considerable success has been reported for conveying visual information to various body parts with tactile stimulation. But there are important considerations to make in this respect. From the perspective of the SOV project, we have from the outset emphasized stimulation of "passive" areas. Our concern has been that the body parts that are used to interact with world, like the face or hands should be free for other use while information from the sensory substitution device is conveyed. For example, stimulation to the tongue can be used effectively and the tongue has high tactile resolution. But generally, users should be able to talk while using a substitution device. Similarly, while the palms and fingertips have very high tactile resolutions, users should also be able to use their hands freely, and anything that interferes with the full use of the hands would have a serious drawback as a sensory substitution device for interacting with the environment. The device should also not be disruptive in the user's environments or intrusive to others. Echolocation, which is in other respects a very useful approach [74], involves sound generation, making this in many respects less than ideal. Note here that the *Sound of Vision* project involved considerable consultation with potential user groups and the seeing-impaired community. One aspect that they emphasized was that any device should not make them stand out in any way, or to as limited an extent as possible.

For example, Kerdagari et al. [75] tested a head-mounted tactile feedback system where their observers navigated along a virtual wall. This is potentially a feasible option for sensory substitution, but head-mounted devices need to ensure that the equipment does not make the user stand out in a crowd. This point is very important since a large concern for the acceptance of such devices in the visually impaired community is that they do not make users stand out as wearing strange equipment as they move around their environments among other people.

The best way of augmenting perceptual input is therefore to stimulate passive areas of the body, such as the back, the forearm, or the waist [14].

8.9 Potential Benefits

Haptic stimulation for sensory substitution from vision can allow observers to have "eyes in the back of their head," so-to-speak because the stimulations can cover all 360° around the observers' head. Something approaching the user from behind could therefore be identified and avoided or interacted with in other ways.

Haptic perception is prone to illusion (see discussion above)—having an element of what Hermann von Helmholtz called "unconscious inference" where interpretative mechanisms of the brain contribute strongly to what is perceived. An excellent example is sensory saltation, also known as the cutaneous rabbit illusion (discussed above; see Fig. 8.4). A set of consequential steps made by something moving along the arm is simply something that makes sense in light of the actual stimulation that is applied. What is then particularly interesting is that our representations are seemingly influenced by *preceding* events [12]. This indicates that perceptual time is not always linear [76, 77]. It is crucial to consider these illusions and what they reveal about perceptual interpretation when sensory substitution devices are designed. But while this presents challenges, it may also provide opportunities where this creative function is utilized.

8.10 Avoiding Sensory Overload

Well-known attentional capacities limit how much information we can process (see [78] for review). Sensory or attentional overload must be avoided. As Loomis et al. [15] have argued, considerable effort and resources has probably been wasted by researchers failing to consider the upper limits of information transmission that can be conveyed within particular perceptual channels. The properties of *modulation transfer functions* (MTF) between different systems must be considered. For example, it is important to consider the bandwidth that a sense allows. In an important investigation, Apkarian-Stielau and Loomis [79] presented alphabetic letters haptically and visually to observers, assessing how discriminable the letters are for each modality. Recognition across the visual and haptic modalities became similar only when the visual presentation was considerably blurred. The resolution was as if a low-pass filter were applied to the tactile stimuli. The MTF for touch therefore obviously involved considerable signal loss, compared to vision, particularly for high frequencies. The bandwidth of the visual system was at least three orders of magnitude larger than for tactile perception. Importantly, this means that haptic devices that exceed two-point thresholds for touch for particular body parts may have been developed ([80, 81]; see discussion in [14, 15]). Note however that two-point thresholds may not place an absolute upper limit on resolution ([14, 54]; see discussion in [44]). Perceptual interpretation can *functionally* result in better resolution than the two-point thresholds would suggest [44]. The so-called *hyperacuity,* where resolution is higher than the dispersion of receptors, e.g., in the retina [82, 83] or the skin [84, 85] indicates that simple one-to-one mapping of input to receptor pattern may not necessarily determine the upper limits of what can potentially be detected.

8.11 Externalization, Generalization, and the Sixth Sense

When we perceive the visual world around us, we do not attribute the visual world to the photons that hit our retina or the air pressure that bends our eardrum—we attribute this to the object that the light is reflected off, or the speaker who causes the changing air pressure. Designers of sensory substitution devices should strive to achieve such *externalization* that the perceiver attributes the stimulation from the sensory substitution device to a distal cause [14, 86] rather than the stimulation being attributed to the device itself. For example, the vibrations and mechanostimulation that occur through the white cane are externalized if the brain attributes the stimulation to the object that the end of the cane hits, not the mechanical stimulation that the cane conveys to the hand [87]. In the case of a sensory substitution, device involving tactile stimulation, the haptic stimulation that is picked up by the mechanical receptors on the skin, needs to be experienced as occurring outside the body—since this is after all the way we perceive the world.

An excellent example of this comes from the so-called out-of-body illusion [88]. Maravita et al. showed that through training, tools can become externalized to the degree that visual-tactile interactions can extend into far space [88]. In particular, they observed this following active training on tool use and that such training can lead to extended representations of the space surrounding the observers [89]. Previously, blindfolded or blind participants in Bach-Y-Rita, [90] who received training on a tactile sensory substitution device that conveyed information about the environment to observers, reported that they were able to literally “see with their skin” [91].

Intriguingly, the information may not need to be from a modality that intact human perceptual systems typically sense, for externalization to occur. Through successful externalization, something approaching another sense can develop. Kaspar et al. [92] used electromagnetic field sensors to feed information about the magnetic pole to users via vibration on a tactile belt. As the observers turned, the tactile stimulator facing north at any given time would vibrate in response to the magnetic pole. After 7 weeks of training many participants reported that the vibrations had become a new source of spatial information—a "sixth sense," so-to-speak.

For any substitution device, it is important that observers learn to *generalize*. This involves that any newly acquired perceptual abilities are extended to new situations (see review in [14]). Arnold and Auvray [93] showed how important it is to train users on a varied set of stimuli to achieve generalizability: increased difficulty of a tactile task involving tactile alphanumeric characters (where the size of the learning set was increased) led to better generalization (see [86]; [94]). It may also be important not to confine the encodings to a one-to-one mapping between the senses. As Kim and Zatorre [94] noted: "as long as tactile space is coded in a systematic way, shape can be conveyed via a medium that is not spatial." A consistent system may suffice for effective sensory substitution.

8.12 Using Multimodal Representations

Studies on multimodal interactions in perception clearly demonstrate that a complete understanding of perceptual representation cannot be achieved without a clear understanding of multisensory interactions [95–101].

But this also provides opportunities, since if our representation of the environment is multimodal, we should not restrict our applications of sensory substitution to a single modality which is exactly what we addressed with the *Sound of Vision* system (see above) where observers received feedback about the environment from head-mounted cameras through both audition and tactile stimulation.

Different perceptual channels may be optimally shaped through evolution for conveying particular information. The auditory system has, for example, evolved to detect changes in air pressure within a certain frequency limit. Some forms of information may be better conveyed with audition (e.g., the *intensity* of a stimulus) while other information may be provided with tactile stimulation (e.g., location). Utilizing the fact that our representations of the world are multimodal could then be thought of as using the best of both worlds for a device conveying a unitary representation, such as the Sound of Vision device [49–52, 102]. SOV was aimed at utilizing this multimodality, through the use of both haptics and audition. Tests of the SOV system are yet to be performed where multimodal environmental encodings are compared with unimodal ones since Hoffman et al. [49–51] only presented tests that involved simultaneous presentation of both auditory and tactile information.

8.13 Lack of Use Within Communities of People with Sensory Impairments

A final point that must be addressed is that despite very impressive technological advances in the development of sensory substitution devices, the use of such devices is not yet widespread within communities of people with sensory impairments.

One problem is that although many applications have been developed, often they have not crossed the line from prototype to finished commercial product—which unfortunately is a theme within this field. One reason could be that scientists working on these solutions tend to be interested in the scientific aspects rather than the applied part and are not as interested in business plans as scientific discoveries. Another reason may be conservatism within the communities of intended users. For example, visually impaired people may be used to the white cane and prefer to stick with what has served them well in the past. A third reason may be conservatism within the community of mobility and orientation assistants. A fourth reason is that a good understanding of the properties of perceptual channels is lacking, resulting in sub-optimal designs. This remains a major challenge for sensory substitution.

8.14 Future Applications and Unexplored Avenues

Recent developments may suggest how artificial intelligence can be used to augment sensory substitution [103]. Implementing ways of self-correction through AI for guidance software could provide large benefits.

Another exciting possibility is the use of tactile feedback for balance such as in using sensory substitution for feedback about the position of a prosthetic limb. A big challenge for those with lower-limb prosthetics is to adjust the position of the prosthetic in response to changing terrain, inclines, or when users walk in stairways since they do not receive proprioceptive feedback about the position of their joints [104, 105]. Tactile feedback could, for example, be used to provide information about the position of the prosthetic and its joints. A number of AI-assisted sensory substitution solutions have been proposed in addition to those we discuss above, such as for improving situational awareness in low-visibility environments. This includes assisting firefighters in smoke-filled rooms or pilots or drivers in low-visibility or high-stress situations through smart-seats conveying spatial information through touch. Other options involve supporting operators of unmanned equipment where tactile feedback can enhance precision and control. A related application could be through robot-assisted surgery.

Technology of this sort also has potential in enriching virtual and augmented reality experiences, adding a dimension of sensory input for more realistic and engaging experiences. We also speculate that such technology can aid with sports training, where athletes can receive real-time feedback through tactile cues to improve form or technique, such as posture correction in running or cycling and in physical therapy and rehabilitation, where tactile input can guide motor recovery and retraining for individuals recovering from injuries or neurological conditions. Tactile feedback could also be applied to stress and anxiety management, where wearable devices could deliver calming tactile pulses or vibrations to help individuals relax in high-stress environments.

8.15 Summary

Sensory substitution devices show great promise for improving the quality of life of people with sensory impairments. One important impediment to progress has been a lack of understanding of the perceptual channels involved. In our work on sensory substation devices for the hearing impaired, we have strived to understand tactile perception, focusing on body parts that are not highly active during everyday function. Another crucial consideration is that attentional resources are limited, and sensory overload must be avoided. All of these considerations are, to our minds, crucial for the development of successful and widely used sensory substitution devices.

Acknowledgments and Declarations The research and product development described in this chapter was supported by the European Union Horizon 2020 Research and Innovation Program, the Icelandic Research Fund, the Icelandic Technological Development Fund and the Research Fund of the University of Iceland. The funders had no influence on the research. All the research was carried out in accordance with the requirements of the Icelandic Bioethics committee and the Declaration of Helsinki. The authors declare no competing interests that are relevant to the content of this chapter.

References

1. Friston, K.J.: Variational filtering. NeuroImage. **41**(3), 747–766 (2008)
2. Rock, I.: The Logic of Perception. The MIT Press, Cambridge, MA (1984)
3. Tanrikulu, Ö.D., Chetverikov, A., Hansmann-Roth, S., Kristjánsson, Á.: What kind of empirical evidence is needed for probabilistic mental representations? An example from visual perception. Cognition. **217**, 104903 (2021)
4. Al-Haytham, I.: Optics. (Transl. A.I. Sabra), London: The Warburg Institute (1039/1978)
5. Berkeley, G.: A Treatise Concerning the Principles of Human Knowledge. London: Oxford University Press (1710/1926)
6. Locke, J.: An Essay Concerning Human Understanding. (Peter H. Nidditch Editor). Oxford: Oxford University Press (1690/1975)
7. Wade, N.J.: A Natural History of Vision. MIT Press, Cambridge, Mass (1998)
8. Meltzoff, A.N., Borton, R.W.: Intermodal matching by human neonates. Nature. **282**(5737), 403–404 (1979). https://doi.org/10.1038/282403a0
9. Versace, E., Freeland, L., Emmerson, M.G.: First-sight recognition of touched objects shows that chicks can solve Molyneux's problem. Biol. Lett. **20**(4) (2024). https://doi.org/10.1098/rsbl.2024.0025

10. Fine, I., Wade, A.R., Brewer, A.A., May, M.G., Goodman, D.F., Boynton, G.M., Wandell, B.A., MacLeod, D.I.: Long-term deprivation affects visual perception and cortex. Nat. Neurosci. **6**(9), 915–916 (2003). https://doi.org/10.1038/nn1102
11. Darwin, C.: The Expression of the Emotions in Man and Animals, 3rd edn. Oxford University Press, New York, Oxford (1998). https://doi.org/10.1017/CBO9780511694110
12. Kristjánsson, Á.: Priming of probabilistic attentional templates. Psychon. Bull. Rev. **30**, 22–39 (2023). https://doi.org/10.3758/s13423-022-02125-w
13. Hoffman, D.D., Singh, M., Prakash, C.: The interface theory of perception. Psychon. Bull. Rev. **22**, 1480–1506 (2015)
14. Kristjánsson, Á., Moldoveanu, A., Jóhannesson, Ó.I., Balan, O., Spagnol, S., Valgeirsdóttir, V.V., Unnthorsson, R.: Designing sensory-substitution devices: principles, pitfalls and potential. Restor. Neurol. Neurosci. **34**(5), 769–787 (2016). https://doi.org/10.3233/RNN-160647
15. Loomis, J.M., Klatzky, R.L., Giudice, N.A.: Assistive Technology for Blindness and Low Vision. CRC Press, Boca Raton, FL (2012). https://doi.org/10.1201/9781315216935
16. Proulx, M.J., Gwinnutt, J., Dell'Erba, S., Levy-Tzedek, S., de Sousa, A.A., Brown, D.J.: Other ways of seeing: from behavior to neural mechanisms in the online "visual" control of action with sensory substitution. Restor. Neurol. Neurosci. **34**(1), 29–44 (2016). https://doi.org/10.3233/RNN-150541
17. Kelley, P. (1999). Historical development of orientation and mobility as a profession: an overview of the development of education, special education and the education of individuals with visual impairments. Retrieved http://www.orientationandmobility.org/profession.html
18. Fodor, J.A.: The Modularity of Mind. MIT Press, Cambridge, MA (1983)
19. Fox, M.D., Snyder, A.Z., Vincent, J.L., Corbetta, M., Van Essen, D.C., Raichle, M.E.: The human brain is intrinsically organized into dynamic, anticorrelated functional networks. Proc. Natl. Acad. Sci. **102**(27), 9673–9678 (2005). https://doi.org/10.1073/pnas.0504136102
20. Friston, K.: Functional integration and inference in the brain. Prog. Neurobiol. **68**(2), 113–143 (2002). https://doi.org/10.1016/s0301-0082(02)00076-x
21. Hyvärinen, J., Carlson, S., Hyvärinen, L.: Early visual deprivation alters modality of neuronal responses in area 19 of monkey cortex. Neurosci. Lett. **26**(3), 239–243 (1981). https://doi.org/10.1016/0304-3940(81)90139-7
22. Held, R., Hein, A.: Movement-produced stimulation in the development of visually guided behavior. J. Comp. Physiol. Psychol. **56**(5), 872–876 (1963)
23. Kujala, T., Palva, M.J., Salonen, O., Alku, P., Huotilainen, M., Järvinen, A., Näätänen, R.: The role of blind humans' visual cortex in auditory change detection. Neurosci. Lett. **379**(2), 127–131 (2005). https://doi.org/10.1016/j.neulet.2004.12.070
24. Poirier, C., Collignon, O., Scheiber, C., Renier, L., Vanlierde, A., Tranduy, D., Veraart, C., De Volder, A.G.: Auditory motion perception activates visual motion areas in early blind subjects. NeuroImage. **31**(1), 279–285 (2006). https://doi.org/10.1016/j.neuroimage.2005.11.036
25. Voss, P., Gougoux, F., Zatorre, R.J., Lassonde, M., Lepore, F.: Differential occipital responses in early- and late-blind individuals during a sound-source discrimination task. NeuroImage. **40**(2), 746–758 (2008). https://doi.org/10.1016/j.neuroimage.2007.12.020
26. Merabet, L.B., Pascual-Leone, A.: Neural reorganization following sensory loss: the opportunity of change. Nat. Rev. Neurosci. **11**(1), 44–52 (2010). https://doi.org/10.1038/nrn2758
27. Pasqualotto, A., Proulx, M.J.: The role of visual experience for the neural basis of spatial cognition. Neurosci. Biobehav. Rev. **36**(4), 1179–1187 (2012). https://doi.org/10.1016/j.neubiorev.2012.01.008
28. Singh, A.K., Phillips, F., Merabet, L.B., Sinha, P.: Why does the cortex reorganize after sensory loss? Trends Cogn. Sci. **22**(7), 569–582 (2018). https://doi.org/10.1016/j.tics.2018.04.004
29. Reich, L., Szwed, M., Cohen, L., Amedi, A.: A ventral visual stream reading center independent of visual experience. Curr. Biol. **21**(5), 363–368 (2011). https://doi.org/10.1016/j.cub.2011.01.040
30. Saccone, E.J., Tian, M., Bedny, M.: Developing cortex is functionally pluripotent: evidence from blindness. Dev. Cogn. Neurosci. **66**, 101360 (2024)

31. Kim, J.S., Kanjlia, S., Merabet, L.B., Bedny, M.: Development of the visual word form area requires visual experience: evidence from blind braille readers. J. Neurosci. **37**(47), 11495–11504 (2017)
32. Ortiz, T., Poch, J., Santos, J.M., Requena, C., Martínez, A.M., Ortiz-Terán, L., Turrero, A., Barcia, J., Nogales, R., Calvo, A., Martínez, J.M., Córdoba, J.L., Pascual-Leone, A.: Recruitment of occipital cortex during sensory substitution training linked to subjective experience of seeing in people with blindness. PLoS One. **6**(8), e23264 (2011). https://doi.org/10.1371/journal.pone.0023264
33. Goyal, M.S., Hansen, P.J., Blakemore, C.B.: Tactile perception recruits functionally related visual areas in the late-blind. Neuroreport. **17**(13), 1381–1384 (2006). https://doi.org/10.1097/01.wnr.0000227990.23046.fe
34. Ratan Murty, N.A., Teng, S., Beeler, D., Mynick, A., Oliva, A., Kanwisher, N.: Visual experience is not necessary for the development of face-selectivity in the lateral fusiform gyrus. Proc. Natl. Acad. Sci. **117**(37), 23011–23020 (2020). https://doi.org/10.1073/pnas.2004607117
35. Kanjlia, S., Loiotile, R.E., Harhen, N., Bedny, M.: 'Visual' cortices of congenitally blind adults are sensitive to response selection demands in a go/no-go task. NeuroImage. **236**, 118023 (2021). https://doi.org/10.1016/j.neuroimage.2021.118023
36. Abboud, S., Cohen, L.: Distinctive interaction between cognitive networks and the visual cortex in early blind individuals. Cereb. Cortex. **29**(11), 4725–4742 (2019). https://doi.org/10.1093/cercor/bhz006
37. Bola, Ł., Yang, H., Caramazza, A., Bi, Y.: Preference for animate domain sounds in the fusiform gyrus of blind individuals is modulated by shape-action mapping. Cereb. Cortex. **32**(21), 4913–4933 (2022). https://doi.org/10.1093/cercor/bhab524
38. Mattioni, S., Rezk, M., Battal, C., Vadlamudi, J., Collignon, O.: Impact of blindness onset on the representation of sound categories in occipital and temporal cortices. eLife. **11**, e79370 (2022). https://doi.org/10.7554/eLife.79370
39. Mattioni, S., Rezk, M., Battal, C., Bottini, R., Cuculiza Mendoza, K.E., Oosterhof, N.N., Collignon, O.: Categorical representation from sound and sight in the ventral occipito-temporal cortex of sighted and blind. eLife. **9**, e50732 (2020). https://doi.org/10.7554/eLife.50732
40. Rączy, K., Urbańczyk, A., Korczyk, M., Szewczyk, J.M., Sumera, E., Szwed, M.: Orthographic priming in braille reading as evidence for task-specific reorganization in the ventral visual cortex of the congenitally blind. J. Cogn. Neurosci. **31**(7), 1065–1078 (2019). https://doi.org/10.1162/jocn_a_01407
41. Van Erp, J.B., Van Veen, H.A., Jansen, C., Dobbins, T.: Waypoint navigation with a vibrotactile waist belt. ACM Trans. Appl. Percept. **2**(2), 106–117 (2005)
42. Cosgun, A., Sisbot, E.A., Christensen, H.I.: Evaluation of rotational and directional vibration patterns on a tactile belt for guiding visually impaired people. In: 2014 IEEE Haptics Symposium (HAPTICS), Houston, TX, USA, pp. 367–370 (2014)
43. Segond, H., Weiss, D., Kawalec, M., Sampaio, E.: Perceiving space and optical cues via a visuo-tactile sensory substitution system: a methodological approach for training of blind subjects for navigation. Perception. **42**(5), 508–528 (2013). https://doi.org/10.1068/p6339
44. Bach-y-Rita, P., Kercel, S.W.: Sensory substitution and the human-machine interface. Trends Cogn. Sci. **7**(12), 541–546 (2003). https://doi.org/10.1016/j.tics.2003.10.013
45. Descartes, R.: The Philosophical Writings of Descartes, vol. 1. Cambridge University Press (1985)
46. Saevarsson, S., Halsband, U., Kristjansson, A.: Designing rehabilitation programs for neglect: could 2 be more than 1+1? Appl. Neuropsychol. **18**(2), 95–106 (2011). https://doi.org/10.1080/09084282.2010.547774
47. Singh-Curry, V., Husain, M.: Cognitive Neurorehabilitation: Evidence and Application, 2nd edn, pp. 449–463 (2008). https://doi.org/10.1017/CBO9781316529898.032
48. Brooks, J., Kristjánsson, Á., Unnthorsson, R.: Sensory Substitution: Visual Information via Haptics, vol. 196. Springer US, New York, NY (2023). https://doi.org/10.1007/978-1-0716-3068-6_14

49. Hoffmann, R., Brinkhuis, M.A., Kristjánsson, Á., Unnthorsson, R.: Introducing a new haptic illusion to increase the perceived. In: 2nd International Conference on Computer-Human Interaction Research and Applications CHIRA, Seville, Spain, vol. 1, pp. 45–53 (2018a). https://doi.org/10.5220/0006899700450053
50. Hoffmann, R., Valgeirsdóttir, V.V., Jóhannesson, Ó.I., Unnthorsson, R., Kristjánsson, Á.: Measuring relative vibrotactile spatial acuity: effects of tactor type, anchor points and tactile anisotropy. Exp. Brain Res. (2018b). https://doi.org/10.1007/s00221-018-5387-z
51. Hoffmann, R., Spagnol, S., Kristjánsson, Á., Unnthorsson, R.: Evaluation of an audio-haptic sensory substitution device for enhancing spatial awareness for the visually impaired. Optom. Vis. Sci. **95**(9), 757–765 (2018c). https://doi.org/10.1097/OPX.0000000000001284
52. Jóhannesson, Ó.I., Balan, O., Unnthorsson, R., Moldoveanu, A., Kristjánsson, Á.: The sound of vision project: on the feasibility of an audio-haptic representation of the environment, for the visually impaired. Brain Sci. **6**(3), 20 (2016). https://doi.org/10.3390/brainsci6030020
53. Jóhannesson, Ó.I., et al.: Relative vibrotactile spatial acuity of the torso. Exp. Brain Res. **235**(11), 3505–3515 (2017). https://doi.org/10.1007/s00221-017-5073-6
54. Novich, S.D., Eagleman, D.M.: Using space and time to encode vibrotactile information: toward an estimate of the skin's achievable throughput. Exp. Brain Res. **233**(10), 2777–2788 (2015). https://doi.org/10.1007/s00221-015-4346-1
55. van Erp, J.B., Verschoor, M.H.: Cross-modal visual and vibrotactile tracking. Appl. Ergon. **35**(2), 105–112 (2004). https://doi.org/10.1016/j.apergo.2003.12.00
56. Makarov, I., Stefánsson Thors, S.S., Ævarsson, E.A., Pind, F.K., Yeganeh, N., Kristjánsson, Á., Unnthorsson, R.: The haptic intensity order illusion is caused by amplitude changes. ACM Trans. Appl. Percept. **21**(1), 1–18 (2023). https://doi.org/10.1145/36262
57. Ævarsson, E.A., Ásgeirsdóttir, T., Pind, F., Kristjánsson, Á., Unnthorsson, R.: Vibrotactile threshold measurements at the wrist using parallel vibration actuators. ACM Trans. Appl. Percept. **19**(3), 1–11 (2022). https://doi.org/10.1145/352925
58. Ackerley, R., Carlsson, I., Wester, H., Olausson, H., Backlund Wasling, H.: Touch perceptions across skin sites: differences between sensitivity, direction discrimination and pleasantness. Front. Behav. Neurosci. **8**, 54 (2014). https://doi.org/10.3389/fnbeh.2014.00054
59. Yeganeh, N., Makarov, I., Stefánsson Thors, S.S., Kristjánsson, Á., Unnthorsson, R.: Evaluating the optimum distance between voice coil actuators using the relative point localization method on the forearm. Actuators. **12**(1), 6 (2023a). https://doi.org/10.3390/act12010006
60. Yeganeh, N., Makarov, I., Unnthorsson, R., Kristjánsson, Á.: Effects of stimulus frequency and location on vibrotactile discrimination performance using voice coil actuators on the forearm. Actuators. **12**(6), 224 (2023b). https://doi.org/10.3390/act12060224
61. Yeganeh, N., Makarov, I., Kristjánsson, Á., Unnthorsson, R.: Discrimination accuracy of sequential versus simultaneous vibrotactile stimulation on the forearm. Appl. Sci. **14**(1), 43 (2024). https://doi.org/10.3390/app14010043
62. Hoffmann, R., Brinkhuis, M.A.B., Unnthorsson, R., Kristjánsson, Á.: The intensity order illusion: temporal order of different vibrotactile intensity causes systematic localization errors. J. Neurophysiol. **122**(4), 1810–1820 (2019). https://doi.org/10.1152/jn.00125.2019
63. Brooks, J., Trojan, J.: The cutaneous rabbit effect: phenomenology and saltation. Scholarpedia. **12**(12), 52363 (2017). https://doi.org/10.4249/scholarpedia.52363
64. Geldard, F., Sherrick, C.: The cutaneous "Rabbit": a perceptual illusion. Sci. New Ser. **178**(4057), 178–179 (1972). https://doi.org/10.1126/science.178.4057.178
65. Gardner, E.P., Spencer, W.A.: Sensory funneling. I. Psychophysical observations of human subjects and responses of cutaneous mechanoreceptive afferents in the cat to patterned skin stimuli. J. Neurophysiol. **35**(6), 925–953 (1972). https://doi.org/10.1152/jn.1972.35.6.925
66. Rahal, L., Cha, J., El Saddik, A., Kammerl, J., Steinbach, E.: Investigating the influence of temporal intensity changes on apparent movement phenomenon. In: 2009 IEEE International Conference on Virtual Environments, Human-Computer Interfaces and Measurements Systems, Hong Kong, China, pp. 310–313 (2009). https://doi.org/10.1109/VECIMS.2009.5068914

67. Day, R.H., Mitchell, P., Stecher, E.J.: The Bourdon illusion occurs with straight-, right-angle-, and parallel-edge figures. Percept. Psychophys. **48**(4), 375–381 (1990). https://doi.org/10.3758/bf03206690
68. Millar, S., Al-Attar, Z.: The Müller-Lyer illusion in touch and vision: implications for multisensory processes. Percept. Psychophys. **64**, 353–365 (2002). https://doi.org/10.3758/BF03194709
69. Ziat, M., Smith, E., Brown, C., DeWolfe, C., Hayward, V.: Ebbinghaus illusion in the tactile modality. In: 2014 IEEE Haptics Symposium (HAPTICS), Houston, TX, USA, 2014, pp. 581–585 (2014). https://doi.org/10.1109/HAPTICS.2014.6775520
70. Lechelt, E., Borchert, R.: The interdependence of time and space in somesthesis: the Tau effect reexamined. Bull. Psychon. Soc. **10**, 191–193 (1977)
71. Yoji, S.: The effect of space on time estimation (S-effect) in tactual space (II). Jpn. J. Psychol. **22**, 189–201 (1952) https://api.semanticscholar.org/CorpusID:147243076
72. Sherrick, C.R.: Apparent haptic movement. Percept. Psychophys. **175–180** (1966). https://doi.org/10.3758/BF03215780
73. Perrotta, M., Ásgeirsdóttir, T., Eagleman, D.: Deciphering sounds through patterns of vibration on the skin. Neuroscience. **15**(458), 77–86 (2021). https://doi.org/10.1016/j.neuroscience.2021.01.008
74. Thaler, L., Goodale, M.A.: Echolocation in humans: an overview. Wiley Interdiscip. Rev. Cogn. Sci. **7**(6), 382–393 (2016)
75. Kerdegari, H., Kim, Y., Prescott, T.J.: Head-mounted sensory augmentation device: designing a tactile language. IEEE Trans. Haptics. **9**(3), 376–386 (2016). https://doi.org/10.1109/TOH.2016.2554111
76. Dennett, D.C., Kinsbourne, M.: Time and the observer: the where and when of consciousness in the brain. Behav. Brain Sci. **15**(2), 183–201 (1992). https://doi.org/10.1017/S0140525X00068229
77. Libet, B., Wright, E.W., Feinstein, B., Pearl, D.K.: Subjective referral of the timing for a conscious sensory experience. Brain. **102**, 193–224 (1979)
78. Kristjánsson, Á., Egeth, H.: How feature integration theory integrated cognitive psychology, neurophysiology, and psychophysics. Atten. Percept. Psychophys. **82**(1), 7–23 (2020). https://doi.org/10.3758/s13414-019-01803-7
79. Apkarian-Stielau, P., Loomis, J.M.: A comparison of tactile and blurred visual form perception. Percept. Psychophys. **18**(5), 362–368 (1975). https://doi.org/10.3758/BF03211213
80. Weinstein, S.: Intensive and extensive aspects of tactile sensitivity as a function of body part, sex, and laterality. In: The Skin Senses, pp. 195–222 (1968)
81. Gardner, E.P., Kandel, E.R.: Touch. In: Kandel, E.R., Schwartz, J.H., Jessell, T.M. (eds.) Principles of Neural Science, 4th edn, pp. 451–471. McGraw-Hill, New York (2000)
82. Fahle, M., Poggio, T.: Visual hyperacuity: spatiotemporal interpolation in human vision. Royal Soc. **213**(1193), 451–477 (1981). https://doi.org/10.1098/rspb.1981.0075
83. Westheimer, G., McKee, S.P.: Visual acuity in the presence of retinal-image motion. J. Opt. Soc. Am. **65**(7), 847–850 (1975). https://doi.org/10.1364/josa.65.000847
84. Duncan, R.O., Boynton, G.M.: Tactile hyperacuity thresholds correlate with finger maps in primary somatosensory cortex (S1). Cereb. Cortex. **17**(12), 2878–2891 (2007)
85. Loomis, J.M.: An investigation of tactile hyperacuity. Sens. Processes. **3**(4), 289–302 (1979)
86. Hartcher-O'Brien, J., Auvray, M.: The process of distal attribution is illuminated through studies of sensory substitution. Multisens. Res. **27**(5–6), 421–441 (2014). https://doi.org/10.1163/22134808-00002456
87. Serino, A., Bassolino, M., Farnè, A., Làdavas, E.: Extended multisensory space in blind cane users. Psychol. Sci. **18**(7), 642–648 (2007). https://doi.org/10.1111/j.1467-9280.2007.01952.x
88. Maravita, A., Husain, M., Clarke, K., Driver, J.: Reaching with a tool extends visual-tactile interactions into far space: evidence from cross-modal extinction. Neuropsychologia. **39**(6), 580–585 (2001). https://doi.org/10.1016/s0028-3932(00)00150-0

89. Maravita, A., Spence, C., Driver, J.: Multisensory integration and the body schema: close to hand and within reach. Curr. Biol. **13**(13), R531–R539 (2003). https://doi.org/10.1016/s0960-9822(03)00449-4
90. Bach-y-Rita, P., Collins, C.C., Saunders, F.A., White, B., Scadden, L.: Vision substitution by tactile image projection. Nature. **221**(5184), 963–964 (1969). https://doi.org/10.1038/221963a0
91. White, B.W., Saunders, F.A., Scadden, L., Bach-Y-Rita, P., Collins, C.C.: Seeing with the skin. Percept. Psychophys. **7**(1), 23–27 (1970). https://doi.org/10.3758/BF03210126
92. Kaspar, K., König, S., Schwandt, J., König, P.: The experience of new sensorimotor contingencies by sensory augmentation. Conscious. Cogn. **28**, 47–63 (2014)
93. Arnold, G., Auvray, M.: Tactile recognition of visual stimuli: specificity versus generalization of perceptual learning. Vis. Res. **152**, 40–50 (2018). https://doi.org/10.1016/j.visres.2017.11.007
94. Kim, J.-K., Zatorre, R.J.: Can you hear shapes you touch? Exp. Brain Res. **202**, 747–754 (2010). https://doi.org/10.1007/s00221-010-2178-6
95. Deroy, O., Chen, Y.-C., Spence, C.: Multisensory constraints on awareness. Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci. **369**(1641) (2014). https://doi.org/10.1098/rstb.2013.0207
96. Driver, J., Noesselt, T.: Multisensory interplay reveals crossmodal influences on 'sensory-specific' brain regions, neural responses, and judgments. Neuron. **57**(1), 11–23 (2008). https://doi.org/10.1016/j.neuron.2007.12.013
97. Driver, J., Spence, C.: Multisensory perception: beyond modularity and convergence. Curr. Biol. **10**(20), R731–R735 (2000). https://doi.org/10.1016/s0960-9822(00)00740-5
98. Koelewijn, T., Bronkhorst, A., Theeuwes, J.: Attention and the multiple stages of multisensory integration: a review of audiovisual studies. Acta Psychol. **134**(3), 372–384 (2010). https://doi.org/10.1016/j.actpsy.2010.03.010
99. Kristjánsson, T., Thorvaldsson, T.P., Kristjánsson, Á.: Divided multimodal attention sensory trace and context coding strategies in spatially congruent auditory and visual presentation. Multisens. Res. **27**(2), 91–110 (2014). https://doi.org/10.1163/22134808-00002448
100. Makarov, I., Unnthorsson, R., Kristjánsson, Á., Thornton, I.M.: The effects of visual and auditory synchrony on human foraging. Atten. Percept. Psychophys. **86**(3), 909–930 (2024). https://doi.org/10.3758/s13414-023-02840-z
101. Stein, B.E., Alex, M., M.: The Merging of the Senses. The MIT Press, Cambridge, MA (1993)
102. Esenkaya, T., Esenkaya, V.L., O'Neill, E., Proulx, M.J.: Multisensory inclusive design with sensory substitution. Cogn. Res.: Princ. Implic. **5**(1), 37 (2020). https://doi.org/10.1186/s41235-020-00240-7
103. Longin, L., Deroy, O.: Augmenting perception: How artificial intelligence transforms sensory substitution. Conscious. Cogn. **99**, 103280 (2022). https://doi.org/10.1016/j.concog.2022.103280
104. Sie, A., Boe, D., Rombokas, E.: Design and evaluation of a wearable haptic feedback system for lower limb prostheses during stair descent. In: 2018 7th IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob), Enschede, Netherlands, pp. 219–224 (2018). https://doi.org/10.1109/BIOROB.2018.8487652
105. Sie, A., Realmuto, J., Rombokas, E.: A lower limb prosthesis haptic feedback system for stair descent. In: Proceedings of the 2017 Design of Medical Devices Conference. 2017 Design of Medical Devices Conference, Minneapolis, Minnesota, USA, 2017, April 10–13, p. 2 (2017). https://doi.org/10.1115/DMD2017-3409