

CHAPTER 4

Multisensory Perception and the Coding of Space

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Vision, audition, and touch all code the space around us, or rather the things that are located in the space around us, in a different way. Yet, together our senses form a coherent spatial representation of our environment. In this chapter we will discuss how space is coded through vision, audition, and touch, and how spatial information from these senses is combined or integrated. We will continue by discussing neuropsychological impairments that affect spatial perception and multisensory integration, and finally how multisensory stimulation may help reduce or overcome some of these impairments.

4.1 HOW VISION, TOUCH, AND AUDITION CODE SPACE

Our everyday experiences with the world are dependent on what we see, hear, feel, smell, and taste. In fact, living without any sensory organs seems useless, as we cannot interact with the world around us. Even losing a single sense can have a great impact on our daily lives (also see [Boxes 4.1 and 4.2](#)). The following situation demonstrates how nicely the senses get along ([Fig. 4.1](#)):

Imagine that it is your turn to hit a piñata at one of your friends' birthday parties. You are blindfolded, disorientated, and given a baseball bat. The piñata is dangling just above you, unaware of its fate. As you are blindfolded you will have to trust on auditory and tactile feedback to know whether you have actually hit the thing, much to the entertainment of your friends. You swing the bat randomly, and at your third attempt you suddenly feel some resistance and hear a crackling sound. You take off your blindfold, look up, and victoriously behold the cracked piñata exactly where you knew it was located once you hit it.



Figure 4.1 Knowing when and where you've hit a piñata requires close communication between the senses (Illustration by N. van der Stoep).

Although there does not seem to be anything special about this situation, a closer look at the piñata encounter reveals to us that something special has just happened. You were not aware of it, but your senses coded the space around you in very different ways, and yet, they all indicated the same location of the piñata in three-dimensional (3-D) space. Whereas you temporarily lost your sight you directly knew where to look after the blindfold was removed. This raises the question of how the remaining senses of audition, touch, and proprioception give input to the visual system. Before addressing multisensory integration let us first briefly discuss the basics of spatial localization through vision, audition, and somatosensation.

4.1.1 Vision

We can only see what we can see in the world around us because of our eyes. As obvious as this may sound, it determines the very nature of what is often considered to be the main exteroceptive system of the human brain: vision. Our sense of vision has several unique properties that help us interact efficiently with the world around us. With our eyes we perceive the light that is (or is not) reflected off things in the region of space in front of the

body. As this light falls on the retina, the world around us is initially always coded in a retinotopic reference frame in the case of vision. This means that everything that we see is coded based on where the light reflections of an object in space fall on the retina. This way of representing the visual world can be seen throughout the visual pathway, from subcortical structures like the superior colliculi to the cortical structures like V1 (Grill-Spector & Malach, 2004; Sparks & Nelson, 1987; see also Chapter 2). The retinotopic mapping of visual information means that the region of space that we can see is directly spatially tuned. It allows us to accurately estimate the location of information in 3-D space, and provides size, shape, and texture information. Furthermore, it allows us to see and integrate many things in our visual field (ie, the part of space that we can see) and has many unique qualities such as the ability to differentiate between different colors, intensities, contrasts, textures, and shapes that help us to group and filter visual information (see Chapter 5 for a further discussion of filtering by spatial attention).

BOX 4.1 Lessons From the Blind: How Vision Loss Affects Spatial Cognition

Unfortunately, loss of vision is still a common ailment in the modern world. Estimates are that about 286 million individuals are severely visually impaired, with about 39 million to be considered blind (World Health Organization (WHO) fact sheet August 2014, <http://www.who.int/mediacentre/factsheets/fs282/en/>, see also Cattaneo & Vecchi, 2011; chapter 1: A Sense of Space). Within this population the condition of congenital blindness is rare, but in absolute numbers still makes a considerable amount. Gilbert and Foster (2001) estimated at about 1.4 million blind children in 2001 worldwide.

A central question is how blindness—especially early in life—affects cognition and in particular spatial thinking and behavior. Losing one sense could have various impacts on task performance by the remaining senses and on crossmodal integration in particular. Pavani and Röder (2012) discuss three possibilities for performance changes in the blind (see also Röder & Rosler, 2004).

First there is the option of hypercompensation. Due to higher reliance on the remaining senses these could become enhanced and start to function on a higher level. We may think here of increased tactile acuity in the blind as an example (Wong, Gnanakumaran, & Goldreich, 2011). At a neural level hypercompensation may be achieved by intramodal plasticity, by changes in multisensory brain areas, and by crossmodal plasticity (Pavani & Röder, 2012). In particular the latter has been demonstrated in studies in which the visual cortex of blind individuals becomes engaged in auditory or tactile tasks (Hamilton & Pascual-Leone, 1998; Sadato et al., 1996; Theoret, Merabet, & Pascual-Leone, 2004; Van der Lubbe, Van Mierlo, & Postma, 2010).

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BOX 4.1 Lessons From the Blind: How Vision Loss Affects Spatial Cognition—cont'd

A second possibility is that performance on a certain task in the remaining sensory modalities stays at about the same level, suggesting independence between the lost modality and the remaining ones for the task at hand. [Renier et al. \(2010\)](#) showed that the right middle occipital gyrus in early blind participants was more tuned to auditory and tactile spatial stimuli than to nonspatial ones (the tuning to auditory and tactile inputs by this visual area again a sign of crossmodal plasticity). A similar preference in the right middle occipital gyrus was observed for visual spatial stimuli compared to nonspatial stimuli in sighted participants. Hence the spatial specialization of the extrastriate cortex remains unchanged even though it is driven in the blind by other modalities ([Striem-Amit et al., 2015](#)). The compensation explanation might also include another variant. Namely the lost sense does have some impact on task performance but this decrease in performance is masked or compensated for by changes in the contributions of other sensory modalities. There are several aids specifically designed to help the blind orient in the world that make use of this compensation possibility. A classic example is the white cane to support mobility ([Maidenbaum et al., 2014](#); [Maidenbaum, Levy-Tzedek, Chebat, Namer-Furstenberg & Amedi, 2014](#); [Proulx, Ptito, & Amedi, 2014](#)). In their book *Blind Vision: The Neuroscience of Visual Impairment* Cattaneo and Vecchi partly appear to adhere the compensation hypothesis: "... we think that shapes and space are represented in an analog format in the blind ..." ([Cattaneo & Vecchi, 2011](#), p. 2). At the same time though, the authors acknowledge that intrinsic differences between blind and sighted individuals also exist.

A third consequence of losing a sense could be that it actually causes deficiencies in various cognitive domains, other than just the affected sensory modality. Some of these deficiencies might even be perceptual. [Zwiers, Van Opstal, and Cruysberg \(2001\)](#) found that blind participants performed more poorly in auditory localization in the vertical plane. Apparently vision is needed to calibrate the spectral sound cues in the pinnae in order to distinguish higher from lower in the vertical dimension. This again illustrates the importance of multisensory integration. Our senses tend to work together. If one sense becomes defective, performance in the other sensory modalities may drop as well.

Blindness may not only affect perceptual functioning of the remaining senses, it could have an impact at higher cognitive levels in particular. Of special interest here are higher forms of cognition such as mental imagery, spatial reasoning, and spatial memory. Can we really understand space if we cannot see (and never have done so)? Optimal sensory integration theories assume that weights are assigned to different sensory inputs in order to explain behavioral interactions ([Millar, 1994](#)). The weights depend on the precision and salience of an input for the task at hand. Vision as such is typically quite useful for spatial processing because it provides external, distal reference frame cues, often in a parallel, configurational manner, and with high acuity. However, [Millar and Al-Attar \(2005\)](#) demonstrated that

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BOX 4.1 Lessons From the Blind: How Vision Loss Affects Spatial Cognition—cont'd

when concurrent visual information was experimentally manipulated to contain no spatial cues at all, blindfolded participants did not profit from it in a haptic spatial memory task. Hence vision per se is not enough for spatial memory. Its importance lays in the fact that under normal circumstances it offers an abundance of spatial cues. Moreover, offering external spatial haptic cues helped blindfolded participants to memorize irregular sequences of haptic spatial locations (Millar & Al-Attar, 2004). Thus, other modalities can also provide a large repertoire of spatial cues that can be used to remember space.

The last two findings suggest that vision per se is not sufficient nor necessary for building complex spatial representations. This again seems to support the option of compensation. Cattaneo et al. (2008) argue that in spatial reasoning and mental imagery, blind individuals often use different mental strategies. These strategies can still be rather effective even though they differ qualitatively from the cognitive solutions employed by sighted persons. At a neural level this may include functional reorganization of visual brain areas as well as the recruitment of supramodal or multisensory brain regions (Cattaneo et al., 2008).

How fixed are the idiosyncratic strategic biases of blind individuals? In their monumental paper *Vision as a Spatial Sense*, Thinus-Blanc and Gaunet (1997) emphasize that performance levels in spatial tasks depend on the particular strategies employed. Because of visual deprivation early on in life and its accompanying exploration behaviors, blind individuals either may have developed notable preferences to employ certain strategies and avoid others, or alternatively may become limited to just a few strategies (perhaps also implying the existence of a critical period to master spatial strategies). The former option is interesting because it may inspire education and training programs for the blind focusing on learning more optimal strategies to deal with spatial tasks.

Is vision a *sine qua non* for spatial cognition (see also Box 1.4)? Is compensation effective enough? Without doubt, vision is very important for understanding, representing, and acting in the spatial world. Congenitally blind clearly do worse on many spatial tests (see Cattaneo et al., 2008, Pasqualotto & Proulx, 2012, for recent overviews). However, at the same time it is also clear that they are not without spatial ability at all and quite often and perhaps surprisingly perform at high levels. Is the difference between blind and sighted individuals just quantitative or also reflecting a qualitative difference? Pasqualotto and Proulx (2012) argue that early visual inputs are essential for full development of multisensory integration abilities, which in turn are important for constructing allocentric spatial and survey representations. While blind do have certain allocentric reference skills (Tinti, Adenzato, Tamietto, & Cornoldi, 2006; Ungar, Blades, & Spencer, 1996), the difference with sighted persons' capacities makes it a large quantitative and even possibly quasiquantitative gap.

4.1.2 Touch

Our sense of touch is mediated by various receptors in the skin that allow us to perceive touch, heat, pressure, pain, etc. (see Chapter 3 for more on touch). As such, touch is always mapped to the body in space. Based on feedback from our muscles we know where in space a body part is located which enables us to know not only on which part of our body we have been touched, but also where in external space we have been touched. Think of, for example, being touched on your right hand both when holding your hand in front of your body and when placing it behind your back. You will be able to tell where on your body you have been touched (on the hand), but also where in external space your hand was when it was touched. When thinking of the region of space within which we can perceive touch, it becomes clear that it is limited in terms of the distance from the body at which we can perceive our environment as compared to, for example, vision and audition.

BOX 4.2 Lessons From the Deaf: How Hearing Loss Affects Spatial Cognition

According to the WHO (2015) around 360 million people worldwide these days suffer from disabling hearing loss (WHO fact sheet March 2015, <http://www.who.int/mediacentre/factsheets/fs300/en/>). The World Federation of the Deaf gives an estimate that about 70 million of these persons are considered deaf (<http://wfdeaf.org/>), that is, suffering a profound hearing loss (over 90 dB in their best ear), with about 32 million of them being children (<http://www.deafchildworldwide.info/>). Deafness in children is often accompanied by multiple other disabilities, either as a consequence of their deafness, or because of an underlying etiology that has several neurocognitive effects, deafness being one of them. The disabilities may include intellectual impairments, autism spectrum disorders, and concurrent perceptual deficits such as deafblindness (Van Dijk, Nelson, Postma, & Van Dijk, 2010). The group of deaf individuals without any comorbid symptoms and with normal intellectual development is particularly interesting. It allows investigating whether their visual abilities function at a superior level (see hypercompensation: Box 4.1) and whether this in turn leads to enhanced spatial abilities.

Deafness appears to incite selective improvements of visual skills, in particular peripheral vision and visual attention, whereas other dimensions remain unchanged (brightness, contrast, movement; Bavelier et al., 2000; Finney & Dobkins, 2001; Lomber, Meredith, & Kral, 2011). Pavani and Bottari (2012)

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BOX 4.2 Lessons From the Deaf: How Hearing Loss Affects Spatial Cognition—cont'd

hypothesize that it is not the visual perception per se that is enhanced but rather visual attention and orienting (see also [Bavelier, Dye, & Hauser, 2006](#)). If visual orienting functions at a higher level in deaf individuals, the possibility emerges that spatial cognition at large is also boosted after hearing deprivation. There are several results suggesting that this is indeed the case ([Emmorey & Kosslyn, 1996](#); [Emmorey, Kosslyn, & Bellugi, 1993](#)). It was reported that deaf individuals have enhanced mental imagery abilities. Importantly, this proficiency seems to depend on the fact that the deaf group used sign language. [Emmorey et al. \(1993\)](#) observed that hearing signers also showed a mental imagery advantage. Similarly, [van Dijk, Kappers, and Postma \(2013a\)](#) reported that both hearing and deaf signers performed better than hearing nonsigners on a haptic configuration learning task but to a similar extent. Sign language is an iconic type of language and has a large intrinsic spatial component (see also Box 6.3). When signing a story with different actors and when relaying a new bit of information about a particular actor, one might want to return to the area of manual action space where previously this actor was first introduced. This requires an implicit or explicit spatial memory. In line with this conjecture it was reported that spatial memory was increased on the basis of both auditory deprivation and (early) sign language experience ([Cattani & Clibbens, 2005](#)).

More research is needed to determine whether auditory deprivation (and subsequent visual attention proficiency) is more important for the development of spatial skills rather than sign language training. This might depend on the precise nature of the spatial task at stake. In contrast to the findings on haptic spatial configuration learning ([van Dijk et al., 2013a](#)), [van Dijk, Kappers, & Postma \(2013b\)](#) found that the same group of deaf participants outperformed both hearing signers and nonsigners on a bimanual haptic orientation matching of two bars that were 120 cm apart in space (see also Fig. 3.5). Hearing signers did not outperform the hearing nonsigners. This may suggest that auditory deprivation is responsible for the haptic orientation matching difference. However, as acknowledged by the authors, as all deaf participants also used sign language, we cannot rule out the possibility that profound sign language training early in life has made the difference. [Cattani and Clibbens \(2005\)](#) also point out the need to include nonsigning deaf participants as well in experimental studies.

It is not surprising that the growth in spatial efficiency with auditory deprivation is accompanied by changes at the brain level. As in the blind brain, major functional reorganization of the brain takes place in deaf individuals ([Kral, 2007](#); [Kral & Eggermont, 2007](#)). Among others the deaf auditory cortex seems to adopt new visual functionality ([Merabet & Pascual-Leone, 2010](#); [Sharma, Nash, & Dorman, 2009](#)). One of the most intriguing patterns of neural

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BOX 4.2 Lessons From the Deaf: How Hearing Loss Affects Spatial Cognition—cont'd

plasticity is the observation of distinct hemispheric lateralization with prolonged auditory deprivation. It has been suggested that in the deaf the left hemisphere becomes more involved in visuospatial tasks that in hearing persons are typically associated with right hemisphere involvement (Bosworth, Petrich, & Dobkins, 2013; Cattaneo, Lega, Cecchetto, & Papagno, 2014). Cattaneo et al. (2014) point out that the default rightward tuning in space perception and representations might be absent in the deaf. Cattani and Clibbens (2005) even found a completely atypical lateralization in deaf participants in certain visuospatial memory conditions. Again, not just deafness itself may contribute to these changes in lateralization, also sign language usage seems to be a factor. Several researchers have claimed that (spatial) language processing by means of sign language causes larger right hemispheric activity (Emmorey et al., 2005; MacSweeney, Capek, Campbell, & Woll, 2008).

Based on the findings from Box 4.1 one might conclude that vision loss seems to depress spatial functioning. In contrast, the take home message from the current box would be that loss of audition strengthens spatial ability. It is remarkable that direct comparisons on spatial tasks between blind and deaf individuals are scarce. The obvious reason for this stems from the fact that the task designs have been adapted for the sense that is lost and thus often are greatly different with respect to input format. One of the few studies directly comparing deaf and blind participants was done by Berg and Worchel (1956). They had sex, age, and intelligence matched deaf, blind, and sighted-hearing children perform two haptic maze tasks. Perhaps surprisingly, deaf individuals performed more poorly than the blind, with sighted/hearing individuals performing better than the blind on one of the two mazes. The authors discussed that verbalization, motor imagery, and visual imagery strategies may all contribute to the performance differences in different extents. van Dijk et al. (2013a) tested deaf signers, hearing signers, and hearing nonsigners on a haptic spatial configuration learning test. They computed Z-scores for the former two groups relative to the performance levels of the third, control group. They also did this for the blind groups in an earlier study from their laboratory (Postma, Zuidhoek, Noordzij, & Kappers, 2007). Fig. 4.2 shows the results of their study. A negative Z-score means better haptic configuration learning relative to the matched controls. It can be seen from Fig. 4.2 that both blind and deaf individuals scored better than their controls (which are at the $Z = 0$ line, the horizontal line in Fig. 4.2). However, this effect was stronger in the blind.

The studies by Berg and Worchel (1956) and van Dijk et al. (2013a) seem to undermine the idea that deafness helps spatial cognition whereas blindness hampers it. However, it should be noted that these tasks were relatively complex and multiple factors play a role other than spatial efficiency. van Dijk et al. (2013a) point out that haptic fluency (handling the shapes by touch) also

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BOX 4.2 Lessons From the Deaf: How Hearing Loss Affects Spatial Cognition—cont'd

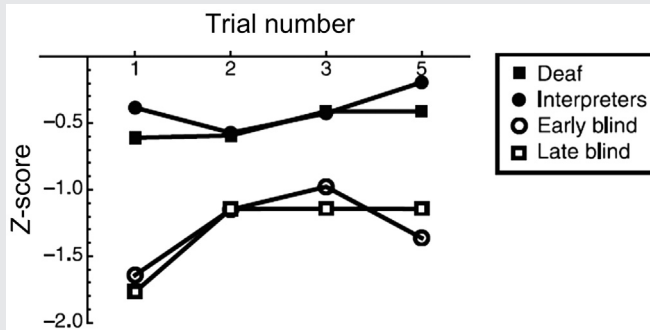


Figure 4.2 Z-scores on a haptic task where shapes have to be put in the corresponding slots on a board by touch. Raw scores over the subsequent trials would have shown any spatial learning effect but the Z-scores displayed here show the relative difference with respect to matched control groups over the various learning trials. It can be seen that the advantage of the blind and deaf groups is highest in the beginning of the experiment. *From van Dijk, R., Kappers, A. M., & Postma, A. (2013a). Haptic spatial configuration learning in deaf and hearing individuals. PLoS One, 8(4), e61336, Figure 4.*

plays a role in their task and can speed up performance. Haptic fluency is clearly better trained in blind participants. Interestingly, a simpler test in which participants had to judge either duration or spatial length of a vibration stimulus on the index fingers revealed blind to be better in temporal judgment than the deaf, whereas the latter seemed to be better on the spatial task (but not significantly so; [Papagno, Cecchetto, Pisoni, & Bolognini, 2016](#)). Clearly further work on the comparison between blind and deaf individuals in spatial cognition is needed, controlling for task complexity, task familiarity, group matching, and the spatial process under scrutiny.

4.1.3 Audition

The localization of sound in space is very different from how we localize visual and tactile information. Whereas vision and somatosensation code space in a more or less direct way (visual space is coded in a retinotopic fashion, see Chapter 2, whereas somatosensation is coded in relation to different body parts, see Chapter 3), the auditory system needs to infer location in a more indirect manner. Two cues that help us localize sounds

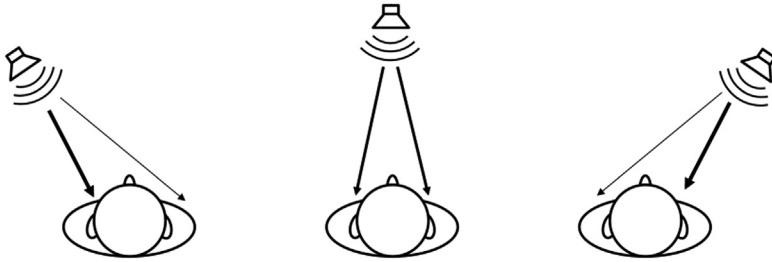


Figure 4.3 (Left) A sound that is presented from the left of the head arrives slightly earlier at the left than the right ear, and its intensity is higher for the left ear than for the right ear. (Center) A sound that is presented from right in front of the body mid-line arrives at both ears simultaneously at the same intensity. (Right) A sound that is presented from the right of the head arrives earlier to and has a higher intensity at the right relative to the left ear.

in horizontal space are interaural time and sound level differences (ITD and ILD; Middlebrooks & Green, 1991). The way our ears are positioned on our head causes a difference in arrival time of a sound at the left and the right ear depending on the position of a sound source relative to the head. Whenever a sound source is located on the right side of the head, a sound wave first arrives at the right ear, and a few microseconds later to the left ear. In contrast, when a sound source is located to the left of the head, a sound wave first arrives at the left ear, and a few milliseconds later to the right ear. Depending on the position of the sound source on the horizontal meridian, the ITD changes, allowing the brain to calculate the lateral position of a sound source in space (Fig. 4.3). Sounds located on the median plane will arrive at the same time at the left and right ear when no objects are in the way.

Another cue to a sound source's position in lateral space is the interaural level difference (ILD). When a sound is located to the right of the head, the sounds' intensity level will be slightly higher at the right ear as compared to the left ear, and vice versa for sounds located to the left of the head (Fig. 4.3).

Although we are generally less accurate in localizing sounds as compared to visual information, we are well able to do so when a sound contains many different frequencies (Frens, Van Opstal, & Van der Willigen, 1995; Middlebrooks & Green, 1991). When a sound consists of only a single frequency we are still able to tell from which horizontal spatial location the sound originated, but it is much harder to determine its elevation. This is because ITD and ILD cues mainly provide information about the location of a sound source in horizontal space. The

localization of sound in the vertical plane (ie, elevation) depends on how the shape of the pinna (ie, the outer ear) affects the spectrum of the sound positioned at various elevations. These monaural spectral cues are also used to distinguish between sound coming from the front and rear space.

The distance of a sound source is estimated based on two types of cues: the intensity of a sound and the direct-to-reverberant ratio of a sound (Bronkhorst & Houtgast, 1999; Middlebrooks & Green, 1991). The intensity of a sound only provides a relative indication of distance when the intensity of a sound source is known. For example, when someone is speaking to you at a regular conversational level (~ 70 dB(A)) it is possible to determine whether someone is close by or further away from you. When we are in enclosed environments such as rooms, sounds not only are arriving directly at our ears, but also arrive in an indirect way because of sound reflections from the walls. It has been shown that we can estimate the absolute distance of a sound based on the ratio between the amplitude of the direct sound and the delay and amplitude of the reflections (Bronkhorst & Houtgast, 1999; see Kolarik, Moore, Zahorik, Cirstea, & Pardhan, 2015, for a review).

4.1.4 Spatial Reference Frames and Their Transformations

As we already mentioned above, vision, audition, and touch are initially all coded in different reference frames. Visual information is processed in a retinotopic reference frame, auditory information in a head-centered reference frame, and touch is coded in a body(-part) centered reference frame. However, to be able to compare spatial information between the senses, sensory information needs to get together at some point during sensory processing and be coded into a common reference frame (Cohen & Andersen, 2002). For example, head-related auditory spatial information needs to be coded into a retinotopic reference frame to make an eye-movement to a sound. Indeed, spatially aligned auditory and visual spatial maps have been found in the super colliculus, a midbrain structure that is heavily involved in generating eye movements (Stein & Meredith, 1993; also see Chapter 5: Spatial Attention and Eye Movements). The parietal cortex also seems to be involved in reference frame transformations for visual, auditory, and tactile information into eye-centered coordinates (ie, a reference frame that takes the orientation of the eyes in the head into account; Cohen & Andersen, 2002). Spatial information from one sense is transformed into the dominant frame of reference of a specific brain region

(Avillac, Deneve, Olivier, Pouget & Duhamel, 2005). These reference frame transformations also allow for comparison of spatial information from different senses regardless of movements of the eyes, head, and the body.

4.2 MULTISENSORY INTEGRATION

Neurophysiological observations of neurons that responded to the stimulation of more than one sense have played an important role in the formulation of various principles of multisensory integration. We will first discuss the neurophysiological principles of multisensory integration. Next, we will discuss behavioral evidence for multisensory integration in humans and its effect on spatial perception.

4.2.1 Principles Underlying Multisensory Integration

Much of the research on multisensory integration has been inspired by neurophysiological studies of the properties of multisensory neurons in monkeys, cats, and rodents (King & Palmer, 1985; Meredith, Nemitz, & Stein, 1987; Stein & Meredith, 1990, 1993). Typically, these studies report that a certain type of multisensory neurons responds to stimuli presented in different modalities. These neurons can be bimodal (eg, responsive to vision and audition) or trimodal (eg, responsive to vision, audition, and touch). Several rules or principles have emerged from these studies, which describe the circumstances under which these multisensory neurons show the largest activity during multisensory stimulation as compared to unimodal stimulation (ie, stimulation of a single sense).

First, multisensory response integration appears most pronounced when the components of a multisensory stimulus (eg, a sound and a light) are presented from the same spatial location (Kadunce, Vaughan, Wallace, & Stein, 2001; Stein & Meredith, 1990; Stein & Stanford, 2008). The influence of spatial alignment on multisensory integration has typically been studied by varying the stimuli in horizontal space (azimuth). However, at least for visual-tactile neurons, it has been shown that the response of multisensory neurons is modulated by the distance between visual and tactile stimuli in depth (Fogassi et al. 1996; Graziano & Gross, 1994). That is, certain multisensory neurons that responded to touch on the face only responded to visual stimuli that were presented within a limited distance from the face. The spatial region within which visual and tactile stimulation both trigger a response in a multisensory neuron is often referred to as peripersonal space (Fogassi et al., 1996; Graziano & Gross,

1994; Holmes & Spence, 2004; Serino, Canzoneri, & Avenanti, 2011; Van der Stoep et al., 2015; Van der Stoep, Serino, Farnè, Di Luca, & Spence, 2016; see also Chapter 1: A Sense of Space).

A second principle that appears to be important is the temporal proximity of the unisensory component stimuli (Meredith et al., 1987). The closer in time, for example, a sound and light flash are presented, the stronger is the response of multisensory cells. The temporal window within which unisensory stimuli from different senses are still integrated is called *the temporal binding window*. However, not all multisensory neurons follow these principles, as sometimes, multisensory integration can be observed in multisensory neurons, even with quite large spatial and temporal misalignment of the component unimodal stimuli (King & Palmer, 1985).

A third principle is called the principle of inverse effectiveness, which states that the relative increase in the activity of multisensory neurons due to multisensory stimulation is much larger when the unisensory component stimuli only evoke a weak response in the neuron (compare Fig. 4.4A–C, eg, a dim light and a soft sound) as compared to stronger stimuli (eg, a bright light and loud sound; Holmes, 2007, 2009; Meredith & Stein, 1983; Stein & Stanford, 2008). Due to inverse effectiveness weak signals are boosted more due to integration and have a higher probability of being perceived (Frassinetti, Pavani, & Ladavas, 2002, 2005; Lovelace, Stein, & Wallace, 2003). The absolute amount of activity in multisensory neurons will, however, be higher when the unisensory component stimuli produce a strong response in the neuron (see Fig. 4.4A).

4.2.2 Principles of Multisensory Integration in Human Behavior

The three main principles of multisensory integration that have been mentioned above have also been studied in humans. There is substantial support for each principle in human multisensory perception. For example, the principle of temporal alignment comes from studies of temporal order judgment (TOJ) and simultaneity perception (Vroomen & Keetels, 2010). When participants have to indicate which of two sequentially presented stimuli appeared first, the sound or the light signal, they generally cannot tell which came first when the sound and light are presented in close temporal proximity. Thus, stimuli that are presented within a temporal binding window are perceived as simultaneous, which could be taken as evidence of a temporal window of integration. The temporal binding window allows for some asynchrony between stimuli

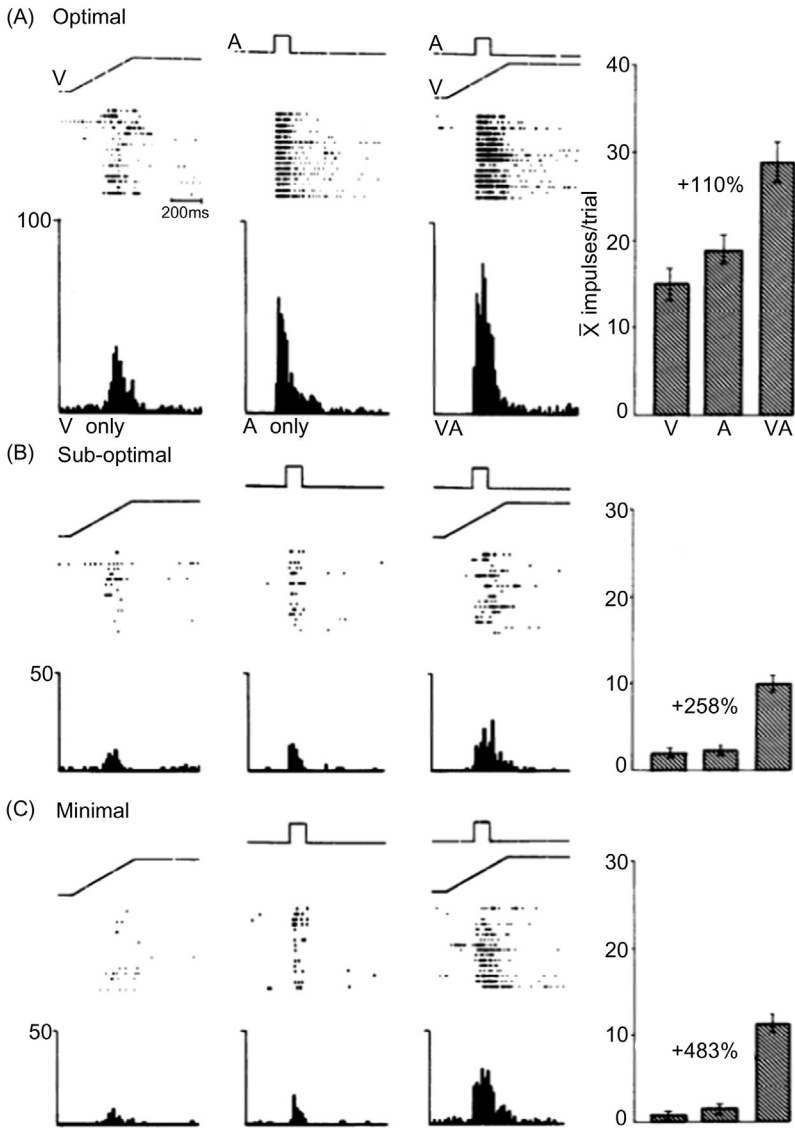


Figure 4.4 The principle of inverse effectiveness: The relative increase in spike rate in a multisensory neuron is greater when the unisensory component stimuli evoke a weak response in the neuron (B and C) as compared to when they evoke a strong response. (A) From Meredith, M. A., & Stein, B. E. (1983). Interactions among converging sensory inputs in the superior colliculus. *Science*, 221(4608), 389–391, Figure 8.

from different modalities. Interestingly, how accurate we are in telling which of two stimuli came first depends on whether the sound and light were presented from the same or a different spatial location (Keetels & Vroomen, 2005). This indicates that the temporal binding window is larger when stimuli are presented from the same rather than different spatial locations. When sound and light are presented from the same spatial location the brain tends to integrate the sound and light, making it more difficult to tell them apart. One could also argue that the brain simply has more information from which to tell apart the sound and light when they not only differ in terms of their temporal onset, but also differ in terms of the spatial location. Additional support for the principles of spatial and temporal alignment comes from studies of multisensory response enhancement (MRE). When participants have to respond as quickly as possible to the onset of a sound, a light, or their combination, response times (RTs) are generally much faster in the combined condition relative to the unisensory condition (Colonus & Diederich, 2004; Gondan & Minakata, 2015; Miller, 1982, 1986; Stevenson, Fister, Barnett, Nidiffer & Wallace, 2012). The amount of MRE depends on the spatial and temporal alignment of the sound and the light (Leone & McCourt, 2013; Van der Stoep, Spence, Nijboer, & Van der Stigchel, 2015). The closer in time and space the sound and the light are presented, the larger the facilitation.

Although the results mentioned above, as well as many other findings in humans, are in line with the principles of spatial and temporal alignment, there are also various circumstances in which human behavior diverges from these principles. For example, the importance of the spatial alignment of stimuli for multisensory integration has most often been observed in tasks in which space was somehow task-relevant, but not in tasks in which space was task-irrelevant (see Spence, 2013, for a review). The principles of multisensory integration thus seem to be more flexible in human behavior and can sometimes be task-dependent.

4.2.3 Multisensory Spatial Conflict

In certain circumstances the brain can receive conflicting spatial information from different senses. A typical example is when external loudspeakers of a television set are placed at a large distance from the screen. How does the brain deal with this conflicting information? Although vision is generally dominant in the spatial domain, audition seems to be more accurate in the temporal domain (Chen & Vroomen, 2013; Welch, DuttonHurt & Warren, 1986). The “modality appropriateness hypothesis” states that a

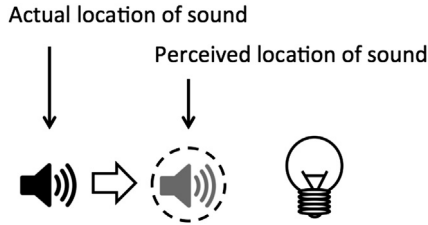


Figure 4.5 In the spatial ventriloquist effect, the perceived location of a sound source is shifted toward a visual source.

sense can dominate perception when it is best suited for a certain task (Spence & Squire, 2003; Welch & Warren, 1980). As a result, visual information can attract the perceived location of a sound that is presented at a slightly different location. This is called the spatial ventriloquist effect (Fig. 4.5). In the case of your television set, you localize sounds next to the screen to a location on the television screen.

In 2002, Marc Ernst and Martin Banks proposed a general principle that determines the degree with which each sense dominates perception. They showed that the contribution of each sense to perception depends on the reliability of sensory information (Alais & Burr, 2004; Battaglia, Jacobs, & Aslin, 2003; Ernst & Banks, 2002). For example, when visual information is more reliable than auditory information, vision mainly determines the perceived spatial location when sound and light are presented at slightly different spatial locations. In contrast, when auditory information is more reliable than visual spatial information, sound mainly determines the perceived spatial location. These findings can be explained by a simple model of optimal combination of visual and auditory spatial information in which the brain weighs auditory and visual information based on the reliability of sensory input. This has also been shown to occur in the depth dimension. When sound and light are presented from slightly different distances from the observer but from the same direction, the location of sounds in depth is perceived at a distance that is closer to the depth at which visual information was presented (Agganis, Muday, & Schirillo, 2010; Bowen, Ramachandran, Muday, & Schirillo, 2011).

4.3 CROSSMODAL EXOGENOUS SPATIAL ATTENTION

The previous section was concerned with how the integration of information from different senses into a unified whole affected spatial perception. However, information from one sense can also affect the perceptual

processing of information from a different sense through crossmodal shifts of exogenous spatial attention (McDonald & Ward, 2000; Spence & Driver, 2004; see Chapter 5 for more information on the effects and different types of attention). For example, a sound (ie, an exogenous auditory cue) can attract attention to its spatial location and facilitate the processing of visual information that is presented a moment later at the same spatial location. Visual information that is presented at a different spatial location than that of the cue is not facilitated, demonstrating the spatial nature of the effects of crossmodal exogenous spatial attention.

By now, the benefits of crossmodal exogenous spatial attention shifts have been demonstrated between all combinations of auditory, visual, and tactile stimuli (Spence & McDonald, 2004). Whereas multisensory integration is typically most pronounced when stimuli from different modalities are presented within close temporal proximity, the beneficial effects of crossmodal shifts of exogenous spatial attention are often most pronounced when there is some time between the stimuli (eg, a ~ 200 ms stimulus onset asynchrony (SOA) between sound and light). Several researchers have suggested that the effects of crossmodal exogenous spatial attention and multisensory integration can be distinguished based on the time course of the facilitation effects of the two processes (McDonald, Teder-Sälejärvi, & Ward, 2001; Van der Stoep et al., 2015). It has been shown that at short SOAs (< 50 ms), crossmodal facilitation is mainly the result of multisensory integration, whereas at intermediate SOAs (~ 50 ms) both crossmodal exogenous spatial attention and multisensory integration contribute to improvements in perception, and at longer SOAs (> 100 ms) crossmodal exogenous spatial attention seems to be the main cause of perceptual benefits (Van der Stoep et al., 2015).

Given the benefits of multisensory integration, researchers wondered whether integrated (multisensory) cues are more effective in attracting spatial attention. This was investigated by comparing the effects of multisensory (audiovisual, audiotactile) and unisensory (auditory, visual, or tactile) exogenous spatial cues (Santangelo, Van der Lubbe, Belardinelli, & Postma, 2006, 2008). At first the effects of multisensory and unisensory cues did not seem to be very different in terms of the benefits of exogenous spatial attention. However, when participants were engaged in a secondary task (ie, doing multiple things at the same time; when the cognitive load was high), multisensory but not unisensory cues could still attract the participants' spatial attention (Santangelo & Spence, 2007; Santangelo, Ho, & Spence, 2008; see Spence & Santangelo, 2009, for a

review). These results indicate a close relationship between multisensory integration and crossmodal exogenous spatial attention.

4.4 MULTISENSORY REGIONS OF SPACE

Although the field of multisensory research has grown rapidly over the last decades, most of the research has focused on multisensory interactions at a fixed distance from the body. Recently, however, researchers started to recognize the importance of the influence of variations in distance on multisensory integration. The brain seems to process information from various regions of space differently (see Fig. 4.6 for the different regions of space; see also Chapter 1: A Sense of Space). The different regions of space can be defined by: (1) the distance at which multisensory interactions between different sensory modalities take place (Occelli, Spence, & Zampini, 2011; Van der Stoep, Nijboer, Van der Stigchel, & Spence, 2015); (2) the behavioral functions that are associated with different regions of space (Previc, 1998; Van der Stoep et al., 2016); and (3) distance-specific impairments in spatial perception (Aimola, Schindler, Simone & Venneri, 2012; Halligan & Marshall, 1991; Van der Stoep et al., 2013).

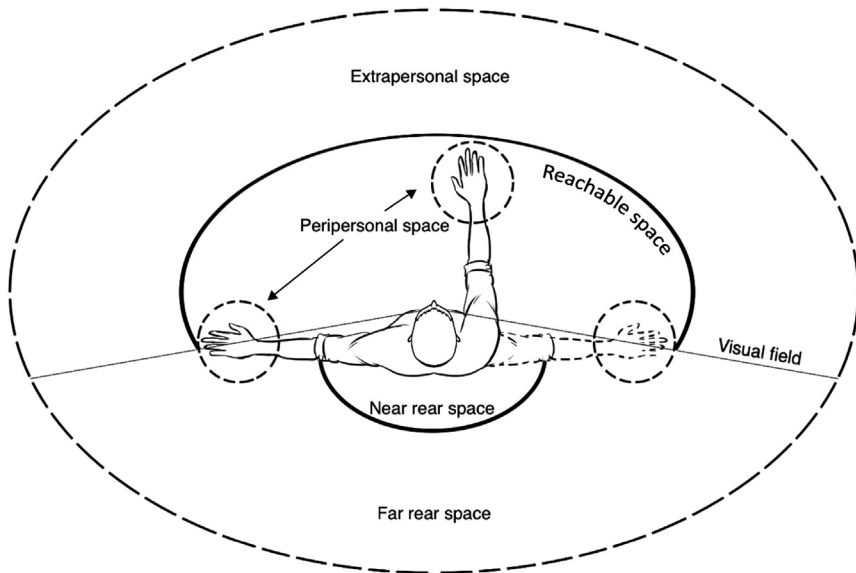


Figure 4.6 A schematic bird's-eye view of the different regions of multisensory space. From Van der Stoep, N., Serino, A., Farnè, A., Di Luca, M., & Spence, C. (2016). *Depth: The forgotten dimension in multisensory research*. Multisensory Research, Figure 1.

4.4.1 Peripersonal Space

About 20 years ago, neurophysiologists observed neurons in the premotor cortex of the macaque monkey that respond to both visual and tactile stimulation (Fogassi et al., 1996; Graziano & Gross, 1994; Graziano, Hu, & Gross, 1997). For example, a neuron could respond to tactile stimulation of the hand and visual stimulation near or on the hand. Importantly, some of these multisensory neurons did not respond to visual stimuli that were presented further away from the hand. The spatial region around the hand within which visual and tactile stimuli evoke a response in multisensory neurons is now commonly termed peripersonal (hand) space. Similar multisensory spatial regions have been observed around the face, shoulders, trunk, and the back of the head (Fogassi et al., 1996; Graziano et al., 1997; Graziano, Reiss, & Gross, 1999; see Graziano & Cooke, 2006, for a review).

There is increasing support for the idea that a peripersonal space around different body parts exists also in humans (see Makin, Holmes, & Ehrsson, 2008; Ocelli et al., 2011; Van der Stoep et al., 2015; Van der Stoep et al., 2016, for reviews). For example, sounds that are close to, rather than far away from, the hand make responses to touch on the hand faster (Canzoneri, Magosso & Serino, 2012; Canzoneri, Ubaldi et al., 2013; Canzoneri, Marzolla, Amoresano, Verni & Serino, 2013). Multisensory interactions in human peripersonal hand space seem to crucially depend on ventral premotor and posterior parietal areas (Serino et al., 2011).

The peripersonal space seems to be flexible in that its size can change depending on the circumstances (Fig. 4.7). For example, tool-use allows interactions between the body and information in extrapersonal space. This novel distance at which interactions with the body can take place seems to trigger a change in the size of peripersonal space to now also incorporate the region of space that was coded as extrapersonal space before tool-use (Berti & Frassinetti, 2000; Farnè, Bonifazi, & Ládavas, 2005; Holmes & Spence, 2004; Van der Stoep et al., 2016). Action preparation (Brozzoli, Ehrsson, & Farnè, 2014), moving through the environment (Galli, Noel, Canzoneri, Blanke, & Serino, 2015; Noel et al., 2015), social interactions (Teneggi, Canzoneri, Di Pellegrino, & Serino, 2013), and anxiety (Lourenco, Longo, & Pathman, 2011; Sambo & Iannetti, 2013; Taffou & Viaud-Delmon, 2014) all seem to be able to change the size or the extent of peripersonal space.

The brain thus seems to flexibly update the space around different body parts within which visual or auditory information can interact with touch on the body. This flexible updating makes sense in that it not only

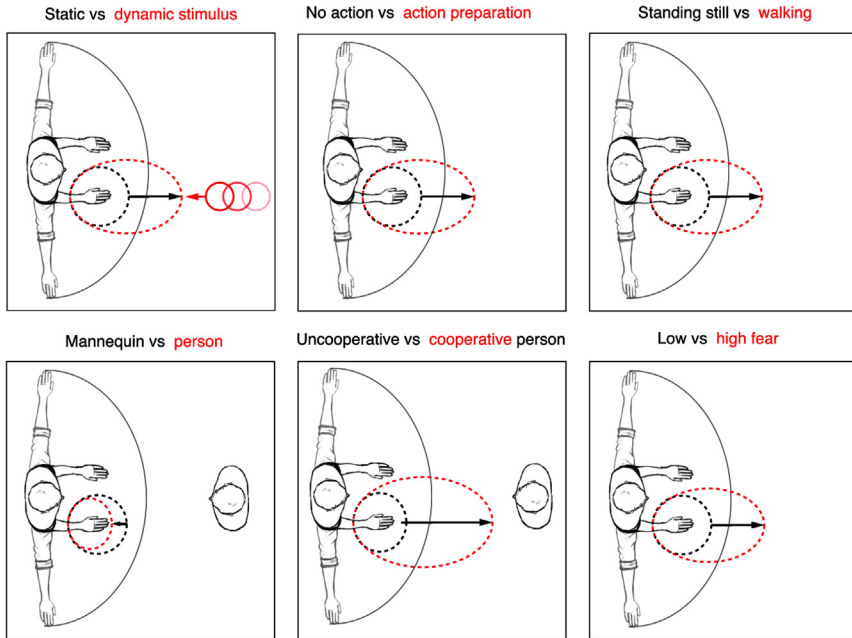


Figure 4.7 A bird's-eye view of how the extent of peripersonal space can change depending on the circumstances. The solid black line represents the reachable space, the dashed black and red circles represent peripersonal hand space in different situations. Taken from Van der Stoep, N., Serino, A., Farnè, A., Di Luca, M., & Spence, C. (2016). *Depth: The forgotten dimension in multisensory research*. Multisensory Research, Figure 3.

allows efficiently responding to and predicting of possible interactions with the environment, but also allows defending the body against potentially harmful interactions with the world.

4.4.2 Extrapersonal Space

Whereas it has become quite clear that multisensory interactions involving touch and vision/audition shape the peripersonal space around different body parts, much less is known about how audiovisual interactions progress in extrapersonal space. Recently, it has been shown that audiovisual interactions are modulated by the distance from which information is presented in extrapersonal space. For example, it was shown that the principle of inverse effectiveness is especially pronounced when decreases in stimulus intensity co-occur with increases in the distance between the stimuli and the observer (Van der Stoep, Van der

Stigchel, Nijboer, & Van der Smagt, 2015). In everyday life, when we view an object from a large distance the retinal image is smaller relative to when we view the object from a smaller distance. Similarly, sounds that we perceive from a closer distance arrive with a higher intensity at our ears than sounds that we perceive from afar. In the study by Van der Stoep, Van der Stigchel, Nijboer, & Van der Smagt, (2015), audiovisual integration was more enhanced when audiovisual stimuli were presented at ~ 2 m as compared to when the exact same stimuli were presented at 80 cm. This could not be explained solely by the principle of inverse effectiveness because presenting stimuli in near space with the same retinal size and auditory/visual intensity did not boost audiovisual integration. Interestingly, a situation in which stimulus size and intensity decrease with distance is quite common in everyday life. Yet, it is not entirely clear as to why audiovisual integration increases in far space. The authors proposed that spatial localization might generally be less reliable in far space, and that the brain therefore benefits more from integrating spatial information from vision and audition in far as compared to near space.

Further support for the idea that the distance from which information is presented in extrapersonal space modulates audiovisual interactions comes from a study of crossmodal exogenous spatial attention (Van der Stoep, Nijboer, & Van der Stigchel, 2014). If sounds can attract spatial attention to a specific location in depth it should only enhance visual information that is presented at that specific location in depth, but not at different distance. This was indeed observed. Sounds that were presented far away facilitated the processing of visual information that was presented at the same depth, but not at a closer distance and vice versa. These results indicate that the distance from which information is presented is taken into account in crossmodal interactions.

4.4.3 Front Versus Rear Space

A region of space that has not been discussed yet is the space behind the body. Audition and touch are dominant in rear space given the lack of visual input. Several studies have shown that sounds that are presented close to the back of the head interact strongly with tactile stimulation of the head. When sounds are presented at a larger distance from the head, the interaction between auditory and tactile information is not as strong (Farnè & Làdavas, 2002). The region of space around the head within

which auditory and tactile information interacts is called the near rear space or rear peripersonal head space. Others have shown that sounds that are presented from behind the body are slightly more effective in attracting a driver's attention to rear space (the rear viewing mirror) than sounds that are presented from front space and vice versa (Ho & Spence, 2005). However, this does not mean that auditory information from rear space cannot affect visual information processing in front space. When participants only had to respond to visual information in front space, auditory cues that were presented in rear space were as effective as the same cues that were presented from front space (Lee & Spence, 2015).

4.5 IMPAIRMENTS IN MULTISENSORY INTEGRATION

As described above, the brain has a large capacity for automatic simultaneous processing and integration of sensory information. Combining information from different sensory modalities can facilitate primary as well as higher order cortical operations such as detection, discrimination, and recognition of sensory stimuli (Ghazanfar & Schroeder, 2006). Multisensory integration helps to create a stable and organized percept of the world and allows for efficient perception of and interaction with the environment. Given the benefits of multisensory integration, an impaired ability to integrate information from different senses may have quite severe consequences for perception and cognitive abilities at large (eg, attention, memory; see Dionne-Dostie, Paquette, Lassonde, & Gallagher, 2015, for a review). For example, recent studies indicate that multisensory integration is impaired in individuals with autism spectrum disorder beyond what would be expected based on already present changes in unisensory processing (Baum, Stevenson, & Wallace, 2015). Difficulties with integrating sensory information may increase distractibility and a general feeling of being quickly overwhelmed by stimuli from the environment. In contrast, multisensory conditions rather than being a problem might also work as a tool to enhance unisensory perception and attention (see Tinga et al., 2015, for a review). Below, we will focus on how multisensory stimulation may or may not improve perception in *sensory* and *attention* disorders such as hemianopia, neglect, and extinction (Heilman, Watson, & Valenstein, 1993).

Losing or being born without one of our senses impairs integrating sensory information from that sense and other, intact, senses because there

is no sensory input from the absent sense. For example, in the blind and the deaf, there is no visual or auditory input, respectively. Interestingly, in these situations the brain can recruit brain regions that are traditionally considered visual or auditory in nature to improve processing of the intact senses (see [Boxes 4.1 and 4.2](#) for more on this topic). However, there are also cases in which vision and/or audition is impaired, but not fully lost. In such cases there may be some residual sensory information processing from the impaired sense, which may still allow the integration of information from the impaired and intact senses. First, we will discuss multisensory processing in a condition that is called hemianopia, or cortical blindness. Next, we will discuss multisensory integration in a condition that is called neglect in which attentional processing is affected. Patients with neglect are typically unaware of visual information in a certain region of space while visual pathways are typically unaffected.

4.5.1 Hemianopia

As a result of lesions in the early visual pathways, patients may fail to adequately respond or report contralesional visual stimuli. This condition is known as hemianopia. Hemianopia has a strong negative impact on several functions and/or activities of daily living, such as reading, scanning a scene or the environment, obstacle avoidance, crossing streets. A few studies have looked into the direct, short-term, as well as longer lasting effects of multisensory stimulation on the performance of patients with subacute and chronic hemianopia. For example, [Frassinetti et al. \(2005\)](#) and [Leo et al. \(2008\)](#) demonstrated that the simultaneous presentation of a sound and light could enhance the detection of a visual target in the blind field of hemianopia patients. In a very recent study, however, no influence of visual stimuli on aurally guided saccades (ie, eye movements to sounds) was observed in patients with hemianopia ([Ten Brink, Nijboer, Bergsma, Barton & Van der Stigchel, 2015](#)). In this study, eight patients with hemianopia had to make eye movements to an auditory target that was either presented in isolation (unisensory condition) or accompanied by a visual stimulus (multisensory condition). The visual stimulus could be presented either at the same or at a different location as the auditory target. Saccade landing points were compared between conditions for each patient. In seven of the eight patients with hemianopia saccade accuracy to the auditory target was influenced by the visual stimulus in the intact field, but not in the blind field. Only

one patient, a patient with quadrantanopia, showed a facilitation effect in the blind quadrant.

Apart from these direct and short-term improvements, longer lasting effects have also been studied. For example, [Bolognini, Rasi, and Lådavas \(2005\)](#) investigated whether auditory localization could be improved using multisensory stimulation in patients with hemianopia. In multisensory trials the sound and light were presented either spatially congruent (ie, same spatial location) or spatially incongruent (ie, different spatial location). Auditory localization improved at all four tested locations (7.5 and 20 degrees in both hemifields). Importantly, the improvement was dependent on the spatial congruency of sound and light signals. These findings are in line with the principle of spatial alignment. Effects were restricted to the contralesional (impaired) visual field.

[Bolognini, Rasi, Coccia, and Lådavas \(2005\)](#) trained patients with hemianopia with audiovisual stimulation, in daily sessions of about 4 h for nearly 2 weeks. During these training sessions, patients had to shift their gaze toward the visual stimulus in the blind hemifield. This visual stimulus was either presented in isolation or accompanied by an auditory stimulus. Patients improved in visual detection, visual exploration, and in different tasks of daily life. Importantly, these improvements were still visible 1 month after the training. Since patients were instructed to make eye movements, multisensory stimulation might have enhanced the responsiveness of the oculomotor system, reinforcing orientation toward the blind hemifield and oculomotor visual exploration, resulting in improved visual detection. This study, however, did not look at the effects of the unimodal versus multisensory conditions. Similar improvement might be obtained by only using unimodal (visual) stimulation, given that each training session contained both unisensory and multisensory stimulation. To investigate the potential benefits of multisensory stimulation over unisensory stimulation, [Passamonti et al. \(2009\)](#) incorporated a unisensory visual control training and compared this to the effects of an audiovisual training. The results indicated that only audiovisual training improved visual detection and exploration, oculomotor scanning and on activities of daily life. These effects remained stable at a 3-month follow-up and a 1-year follow-up. Patients' oculomotor scanning was more similar to the healthy control subjects after audiovisual training, whereas the group of patients receiving the control (visual only) training showed no significant change. These findings indicate a long-term persistence of audiovisual treatment effects on the

oculomotor system, which might encourage a more organized pattern of visual exploration.

In a similar study by Keller and Lefin-Rank (2010) the effects of audiovisual stimulation in patients in the subacute phase after brain damage was studied. Either an audiovisual training or a visual training was given to patients with hemianopia. Patients were instructed to detect visual targets as fast as possible. The audiovisual training resulted in a larger improvement in visual exploration compared to the visual training. Additionally, only patients that received audiovisual training showed near normal daily living activities after training.

Interestingly, proprioceptive stimulation may also help to improve visual detection (Schendel & Robertson, 2004) or target size processing (Brown, Kroliczak, Demonet, & Goodale, 2008). Schendel and Robertson showed that visual detection in the blind field of a single patient improved when the contralesional arm was extended into the blind field, but only when the hand was placed near the visual targets, not when the hand was placed further away. These results could not be replicated, however, in a very similar study by Smith et al. (2008), in which five patients were tested. As for object size estimations, it was shown that performance was significantly improved when the patients' contralesional hand was placed near the objects (Brown et al., 2008). Although some of these results look promising, it should be noted that only very small samples of patients were included in these studies and variation in effect or effect sizes appears to be large.

Although the results of the above mentioned studies look promising with respect to the benefits of multisensory stimulation or training, it is still unclear which patients will benefit from this. Given that some patients have shown no improvements during multisensory stimulation (Ten Brink et al., 2015), isolating the factors that determine whether a patient will benefit from such a multisensory training may help improve and individualize treatment.

4.5.2 Neglect

Neglect is a common disorder that affects approximately 50% of stroke patients in (sub)acute stage after stroke, in which patients are impaired in detecting stimuli or orienting attention toward the contralesional side of space (Bisiach & Luzzatti, 1978; Halligan, Fink, Marshall, & Vallar, 2003; Heilman & Valenstein, 1979; Heilman et al., 1993; Nijboer, Kollen, &

Kwakkel, 2013). Neglect is an important negative prognostic factor for (motor) recovery (Cherney, Halper, Kwasnica, Harvey, & Zhang, 2001; Nijboer, Kollen, & Kwakkel, 2014) and independence in activities of daily living (Nijboer, Van de Port, Schepers, Post, & Visser-Meily, 2013). The current theory is that neglect is better explained by dysfunction of distributed cortical attention networks than by structural damage to specific brain areas (Corbetta & Shulman, 2011; Karnath & Rorden, 2012; Urbanski et al, 2011; see also Chapter 5). The aim of many treatments for neglect is to reduce the imbalance between the two hemispheres. Multisensory stimulation could be such a treatment.

Frassinetti et al. (2005) showed that the combination of visual and auditory stimulation could improve visual detection accuracy in neglect. Seven patients with neglect took place in a setup where four visual stimuli could be presented on the left, and four on the right with respect to body midline of the patients. At the exact same locations as the visual stimuli, auditory stimuli could be presented. Patients were asked to detect the location of the visual stimuli. On average only approximately 18% of the visual stimuli were detected, a percentage that increased to approximately 49% when an auditory stimulus was presented at the same time, at the exact same location. When the auditory stimulus was presented at the same time, but from a different location as the visual stimulus, detection accuracy was approximately 35%. In an earlier study, Frassinetti et al. (2002) showed that the detection accuracy heavily relied on the spatial distance between visual and auditory stimuli. With a comparable setup, seven patients with neglect were asked to indicate the location of a visual stimulus and the accuracy was best when the visual and auditory stimuli were located at the exact same position. When the auditory stimulus was presented from the location directly adjacent to the location of the visual stimulus, performance decreased but was still significantly better compared to no auditory stimulus. With increasing distance from the location of the visual stimuli, the beneficial effect of the auditory stimulus diminished.

Sambo et al. (2011) investigated whether the combination of visual and tactile stimuli could enhance processing of tactile stimuli in patients with visual neglect and tactile extinction. Extinction is related to neglect, but not the same. Patients with extinction will detect stimuli on the left and on the right side, but will ignore stimuli on one side when the left and the right side are presented simultaneously. Extinction can occur in different sensory modalities: visual, auditory, and tactile extinction frequently occur after stroke. In the study by Sambo et al. (2011), patients fixated on a

fixation cross and had to indicate as quickly and accurately as possible when they detected a tactile stimulus. Detection of a tactile stimulus to the left hand was significantly faster when the left hand was placed in the right (ie, intact) visual field compared to the left (ie, neglect) visual field.

Visuo-somatosensory combinations have also been studied in a patient with visual extinction (Di Pellegrino and Frassinetti, 2000). When patients with visual extinction had to report digits on a monitor they reported the digit on the right almost every trial, whereas the stimulus on the left was often ignored. Only when the patient was allowed to place their own hands near the visual stimuli did performance increase significantly. No changes in performance were found when the hands were further away from the stimuli, or when images of hands were presented near the stimuli.

4.6 CONCLUSION

Space is a feature of the world that is shared by our senses: we can see, hear, and feel where things are. Moreover, though not well developed in all humans (and ignored in this book), we also have a coarse sense of smell for direction. In this chapter we started with a brief discussion of how the senses code space. More importantly we have paid attention to the question of how they work together in multisensory integration and crossmodal interactions. We wish to emphasize here that in clinical patient work a very promising approach lies in applying multisensory interventions. Patients with sensory impairments (deaf, blind; see Boxes 4.1 and 4.2) could particularly benefit from applying combinations of stimuli from the remaining senses (see also the use of sensory substitution devices; Maidenbaum et al., 2014; Proulx et al., 2014). Similarly treatment of neurological disorders might entertain multisensory stimulation techniques. Several patient studies have already indicated that multisensory stimulation can enhance performance on several different tasks (eg, detection, localization, search, exploration, some activities of daily living) in which a response is required to sensory stimuli.¹

¹ It should be kept in mind, though, that the studies described here used very small groups of patients and none of the studies were proper randomized controlled trials (RCTs). In this design, usually larger groups of patients are randomly assigned to either the experimental condition or a control or placebo condition. In this case, a placebo condition could be care as usual, where the optimal design would incorporate two experimental conditions: one in which only unisensory stimulation would take place and one in which multisensory stimulation would be given.

Impairments due to stroke may be reduced during multisensory stimulation because multisensory brain regions still function and enhance perceptual processing. In the case of hemianopia, when a patient's visual cortex has been affected by stroke, there may still be some subcortical processing of visual information. In subcortical multisensory brain regions, such as the superior colliculus, multisensory integration can still enhance the analysis of visual input and improve spatial orienting. Given that multiple brain regions are involved in multisensory integration, damage to one unisensory or multisensory brain area may not necessarily lead to an overall impairment in multisensory integration or perception in general. This makes multisensory stimulation a highly interesting candidate for diagnostics and rehabilitation of motor, sensory, or attention deficits (ie, neglect) after stroke.

REFERENCES

- Agganis, B. T., Muday, J. A., & Schirillo, J. A. (2010). Visual biasing of auditory localization in azimuth and depth. *Perceptual and Motor Skills*, *111*(3), 872–892.
- Aimola, L., Schindler, I., Simone, A. M., & Venneri, A. (2012). Near and far space neglect: Task sensitivity and anatomical substrates. *Neuropsychologia*, *50*(6), 1115–1123.
- Alais, D., & Burr, D. (2004). The ventriloquist effect results from near-optimal bimodal integration. *Current Biology*, *14*(3), 257–262.
- Avillac, M., Deneve, S., Olivier, E., Pouget, A., & Duhamel, J. R. (2005). Reference frames for representing visual and tactile locations in parietal cortex. *Nature Neuroscience*, *8*(7), 941–949.
- Battaglia, P. W., Jacobs, R. A., & Aslin, R. N. (2003). Bayesian integration of visual and auditory signals for spatial localization. *Journal of the Optical Society of America A*, *20*(7), 1391–1397.
- Baum, S. H., Stevenson, R. A., & Wallace, M. T. (2015). Behavioral, perceptual, and neural alterations in sensory and multisensory function in autism spectrum disorder. *Progress in Neurobiology*, *134*, 140–160.
- Bavelier, D., Dye, M. W., & Hauser, P. C. (2006). Do deaf individuals see better? *Trends in Cognitive Sciences*, *10*(11), 512–518. wdoi:S1364-6613(06)00243-9.
- Bavelier, D., Tomann, A., Hutton, C., Mitchell, T., Corina, D., Liu, G., & Neville, H. (2000). Visual attention to the periphery is enhanced in congenitally deaf individuals. *Journal of Neuroscience*, *20*(17), RC93.
- Berg, J., & Worchel, P. (1956). Sensory contributions to human maze-learning—A comparison of matched blind, deaf, and normals. *Journal of General Psychology*, *54*(1), 81–93.
- Berti, A., & Frassinetti, F. (2000). When far becomes near: Remapping of space by tool use. *Journal of Cognitive Neuroscience*, *12*(3), 415–420.
- Bisiach, E., & Luzzatti, C. (1978). Unilateral neglect of representational space. *Cortex*, *14*(1), 129–133.
- Bolognini, N., Rasi, F., Coccia, M., & Ládavas, E. (2005). Visual search improvement in hemianopic patients after audio-visual stimulation. *Brain*, *128*(12), 2830–2842.

- Bolognini, N., Rasi, F., & Làdavas, E. (2005). Visual localization of sounds. *Neuropsychologia*, *43*(11), 1655–1661.
- Bosworth, R. G., Petrich, J. A., & Dobkins, K. R. (2013). Effects of attention and laterality on motion and orientation discrimination in deaf signers. *Brain and Cognition*, *82*(1), 117–126. Available from <http://dx.doi.org/10.1016/j.bandc.2013.01.006>.
- Bowen, A. L., Ramachandran, R., Muday, J. A., & Schirillo, J. A. (2011). Visual signals bias auditory targets in azimuth and depth. *Experimental Brain Research*, *214*(3), 403–414.
- Bronkhorst, A. W., & Houtgast, T. (1999). Auditory distance perception in rooms. *Nature*, *397*(6719), 517–520.
- Brown, L. E., Kroliczak, G., Demonet, J. F., & Goodale, M. A. (2008). A hand in blind-sight: Hand placement near target improves size perception in the blind visual field. *Neuropsychologia*, *46*(3), 786–802.
- Brozzoli, C., Ehrsson, H. H., & Farnè, A. (2014). Multisensory representation of the space near the hand from perception to action and interindividual interactions. *The Neuroscientist*, *20*, 122–135.
- Canzoneri, E., Magosso, E., & Serino, A. (2012). Dynamic sounds capture the boundaries of peripersonal space representation in humans. *PLoS One*, *7*, e44306. Available from <http://dx.doi.org/10.1371/journal.pone.0044306>.
- Canzoneri, E., Marzolla, M., Amoresano, A., Verni, G., & Serino, A. (2013). Amputation and prosthesis implantation shape body and peripersonal space representations. *Scientific Reports*, *3*, 2844. Available from <http://dx.doi.org/10.1038/srep02844>.
- Canzoneri, E., Ubaldi, S., Rastelli, V., Finisguerra, A., Bassolino, M., & Serino, A. (2013). Tool-use reshapes the boundaries of body and peripersonal space representations. *Experimental Brain Research*, *228*, 25–42.
- Cattaneo, Z., Lega, C., Cecchetto, C., & Papagno, C. (2014). Auditory deprivation affects biases of visuospatial attention as measured by line bisection. *Experimental Brain Research*, *232*(9), 2767–2773. Available from <http://dx.doi.org/10.1007/s00221-014-3960-7>.
- Cattaneo, Z., & Vecchi, T. (2011). *Blind vision: The neuroscience of visual impairment*. Cambridge, MA, London: MIT Press.
- Cattaneo, Z., Vecchi, T., Cornoldi, C., Mammarella, I., Bonino, D., Ricciardi, E., & Pietrini, P. (2008). Imagery and spatial processes in blindness and visual impairment. *Neuroscience & Biobehavioral Reviews*, *32*(8), 1346–1360. Available from <http://dx.doi.org/10.1016/j.neubiorev.2008.05.002>.
- Cattani, A., & Clibbens, J. (2005). Atypical lateralization of memory for location: Effects of deafness and sign language use. *Brain and Cognition*, *58*(2), 226–239. Available from <http://dx.doi.org/10.1016/j.bandc.2004.12.001>.
- Chen, L., & Vroomen, J. (2013). Intersensory binding across space and time: A tutorial review. *Attention, Perception, & Psychophysics*, *75*(5), 790–811.
- Cherney, L. R., Halper, A. S., Kwasnica, C. M., Harvey, R. L., & Zhang, M. (2001). Recovery of functional status after right hemisphere stroke: Relationship with unilateral neglect. *Archives of Physical Medicine and Rehabilitation*, *82*(3), 322–328.
- Cohen, Y. E., & Andersen, R. A. (2002). A common reference frame for movement plans in the posterior parietal cortex. *Nature Reviews Neuroscience*, *3*(7), 553–562.
- Colonus, H., & Diederich, A. (2004). Multisensory interaction in saccadic reaction time: a time-window-of-integration model. *Journal of Cognitive Neuroscience*, *16*(6), 1000–1009.
- Corbetta, M., & Shulman, G. L. (2011). Spatial neglect and attention networks. *Annual Review of Neuroscience*, *34*, 569.
- di Pellegrino, G., & Frassinetti, F. (2000). Direct evidence from parietal extinction of enhancement of visual attention near a visible hand. *Current Biology*, *10*(22), 1475–1477.

- Dionne-Dostie, E., Paquette, N., Lassonde, M., & Gallagher, A. (2015). Multisensory integration and child neurodevelopment. *Brain Sciences*, 5(1), 32–57.
- Emmorey, K., Grabowski, T., McCullough, S., Ponto, L. L., Hichwa, R. D., & Damasio, H. (2005). The neural correlates of spatial language in English and American Sign Language: A PET study with hearing bilinguals. *Neuroimage*, 24(3), 832–840. Available from <http://dx.doi.org/10.1016/j.neuroimage.2004.10.008>.
- Emmorey, K., & Kosslyn, S. M. (1996). Enhanced image generation abilities in deaf signers: A right hemisphere effect. *Brain and Cognition*, 32(1), 28–44. doi:S0278-2626(96)90056-1.
- Emmorey, K., Kosslyn, S. M., & Bellugi, U. (1993). Visual imagery and visual–spatial language: Enhanced imagery abilities in deaf and hearing ASL signers. *Cognition*, 46(2), 139–181. doi:0010-0277(93)90017-P.
- Ernst, M. O., & Banks, M. S. (2002). Humans integrate visual and haptic information in a statistically optimal fashion. *Nature*, 415(6870), 429–433.
- Farnè, A., Bonifazi, S., & Làdavas, E. (2005). The role played by tool-use and tool-length on the plastic elongation of peri-hand space: A single case study. *Cognitive Neuropsychology*, 22(3–4), 408–418.
- Farnè, A., & Làdavas, E. (2002). Auditory peripersonal space in humans. *Journal of Cognitive Neuroscience*, 14(7), 1030–1043.
- Finney, E. M., & Dobkins, K. R. (2001). Visual contrast sensitivity in deaf versus hearing populations: exploring the perceptual consequences of auditory deprivation and experience with a visual language. *Cognitive Brain Research*, 11(1), 171–183.
- Fogassi, L., Gallese, V., Fadiga, L., Luppino, G., Matelli, M., & Rizzolatti, G. (1996). Coding of peripersonal space in inferior premotor cortex (area F4). *Journal of Neurophysiology*, 76(1), 141–157.
- Frassinetti, F., Bolognini, N., Bottari, D., Bonora, A., & Làdavas, E. (2005). Audiovisual integration in patients with visual deficit. *Journal of Cognitive Neuroscience*, 17(9), 1442–1452.
- Frassinetti, F., Pavani, F., & Ladavas, E. (2002). Acoustical vision of neglected stimuli: Interaction among spatially converging audiovisual inputs in neglect patients. *Journal of Cognitive Neuroscience*, 14(1), 62–69.
- Frens, M. A., Van Opstal, A. J., & Van der Willigen, R. F. (1995). Spatial and temporal factors determine auditory–visual interactions in human saccadic eye movements. *Perception & Psychophysics*, 57(6), 802–816.
- Galli, G., Noel, J. P., Canzoneri, E., Blanke, O., & Serino, A. (2015). The wheelchair as a full-body tool extending the peripersonal space. *Frontiers in Psychology*, 6, 639.
- Ghazanfar, A. A., & Schroeder, C. E. (2006). Is neocortex essentially multisensory? *Trends in Cognitive Sciences*, 10(6), 278–285.
- Gilbert, C., & Foster, A. (2001). Childhood blindness in the context of VISION 2020—the right to sight. *Bulletin World Health Organ*, 79(3), 227–232.
- Gondan, M., & Minakata, K. (2015). A tutorial on testing the race model inequality. *Attention, Perception, & Psychophysics*, 1–13.
- Graziano, M. S., & Cooke, D. F. (2006). Parieto-frontal interactions, personal space, and defensive behavior. *Neuropsychologia*, 44(6), 845–859.
- Graziano, M. S., & Gross, C. G. (1994). The representation of extrapersonal space: A possible role for bimodal, visual–tactile neurons. In M. S. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 1021–1034). Cambridge, MA: MIT Press.
- Graziano, M. S., Hu, X. T., & Gross, C. G. (1997). Visuospatial properties of ventral premotor cortex. *Journal of Neurophysiology*, 77(5), 2268–2292.
- Graziano, M. S., Reiss, L. A., & Gross, C. G. (1999). A neuronal representation of the location of nearby sounds. *Nature*, 397(6718), 428–430.

- Grill-Spector, K., & Malach, R. (2004). The human visual cortex. *Annual Reviews in Neuroscience*, 27, 649–677.
- Halligan, P. W., Fink, G. R., Marshall, J. C., & Vallar, G. (2003). Spatial cognition: Evidence from visual neglect. *Trends in Cognitive Sciences*, 7(3), 125–133.
- Halligan, P. W., & Marshall, J. C. (1991). Left neglect for near but not far space in man. *Nature*, 350(6318), 498–500.
- Hamilton, R. H., & Pascual-Leone, A. (1998). Cortical plasticity associated with Braille learning. *Trends in Cognitive Sciences*, 2(5), 168–174.
- Heilman, K. M., & Valenstein, E. (1979). Mechanisms underlying hemispatial neglect. *Annals of Neurology*, 5(2), 166–170.
- Heilman, K. M., Watson, R. T., & Valenstein, E. (1993). Neglect and related disorders. In K. M. Heilman, & E. Valenstein (Eds.), *Clinical Neuropsychology* (pp. 243–294). New York, NY: Oxford University Press.
- Ho, C., & Spence, C. (2005). Assessing the effectiveness of various auditory cues in capturing a driver's visual attention. *Journal of Experimental Psychology: Applied*, 11(3), 157.
- Holmes, N. P. (2007). The law of inverse effectiveness in neurons and behaviour: Multisensory integration versus normal variability. *Neuropsychologia*, 45(14), 3340–3345.
- Holmes, N. P. (2009). The principle of inverse effectiveness in multisensory integration: Some statistical considerations. *Brain Topography*, 21(3–4), 168–176.
- Holmes, N. P., & Spence, C. (2004). The body schema and multisensory representation(s) of peripersonal space. *Cognitive Processing*, 5(2), 94–105.
- Kadunce, D. C., Vaughan, W. J., Wallace, M. T., & Stein, B. E. (2001). The influence of visual and auditory receptive field organization on multisensory integration in the superior colliculus. *Experimental Brain Research*, 139(3), 303–310.
- Karnath, H. O., & Rorden, C. (2012). The anatomy of spatial neglect. *Neuropsychologia*, 50(6), 1010–1017.
- Keetels, M., & Vroomen, J. (2005). The role of spatial disparity and hemifields in audio-visual temporal order judgments. *Experimental Brain Research*, 167(4), 635–640.
- Keller, I., & Lefin-Rank, G. (2010). Improvement of visual search after audiovisual exploration training in hemianopic patients. *Neurorehabilitation and Neural Repair*, 24(7), 666–673.
- King, A. J., & Palmer, A. R. (1985). Integration of visual and auditory information in bimodal neurones in the guinea-pig superior colliculus. *Experimental Brain Research*, 60(3), 492–500.
- Kolarik, A. J., Moore, B. C., Zahorik, P., Cirstea, S., & Pardhan, S. (2015). Auditory distance perception in humans: A review of cues, development, neuronal bases, and effects of sensory loss. *Attention, Perception, & Psychophysics*, 1–23.
- Kral, A. (2007). Unimodal and cross-modal plasticity in the “deaf” auditory cortex. *International Journal of Audiology*, 46(9), 479–493. Available from <http://dx.doi.org/10.1080/14992020701383027>.
- Kral, A., & Eggermont, J. J. (2007). What's to lose and what's to learn: Development under auditory deprivation, cochlear implants and limits of cortical plasticity. *Brain Research Reviews*, 56(1), 259–269. Available from <http://dx.doi.org/10.1016/j.brainresrev.2007.07.021>.
- Lee, J., & Spence, C. (2015). Audiovisual crossmodal cuing effects in front and rear space. *Frontiers in Psychology*, 6.
- Leone, L. M., & McCourt, M. E. (2013). The roles of physical and physiological simultaneity in audiovisual multisensory facilitation. *i-Perception*, 4(4), 213–228.
- Leo, F., Bolognini, N., Passamonti, C., Stein, B. E., & Làdavas, E. (2008). Cross-modal localization in hemianopia: New insights on multisensory integration. *Brain*, 131(3), 855–865.

- Lomber, S. G., Meredith, M. A., & Kral, A. (2011). Adaptive crossmodal plasticity in deaf auditory cortex: Areal and laminar contributions to supranormal vision in the deaf. *Progress in Brain Research*, *191*, 251–270. Available from <http://dx.doi.org/10.1016/B978-0-444-53752-2.00001-1>.
- Lourenco, S. F., Longo, M. R., & Pathman, T. (2011). Near space and its relation to claustrophobic fear. *Cognition*, *119*(3), 448–453.
- Lovelace, C. T., Stein, B. E., & Wallace, M. T. (2003). An irrelevant light enhances auditory detection in humans: A psychophysical analysis of multisensory integration in stimulus detection. *Cognitive Brain Research*, *17*(2), 447–453.
- MacSweeney, M., Capek, C. M., Campbell, R., & Woll, B. (2008). The signing brain: The neurobiology of sign language. *Trends in Cognitive Sciences*, *12*(11), 432–440. Available from <http://dx.doi.org/10.1016/j.tics.2008.07.010>.
- Maidenbaum, S., Hanassy, S., Abboud, S., Buchs, G., Chebat, D. R., Levy-Tzedek, S., & Amedi, A. (2014). The “EyeCane”, a new electronic travel aid for the blind: Technology, behavior & swift learning. *Restorative Neurology and Neuroscience*, *32*(6), 813–824. Available from <http://dx.doi.org/10.3233/RNN-130351>.
- Maidenbaum, S., Levy-Tzedek, S., Chebat, D. R., Namer-Furstenberg, R., & Amedi, A. (2014). The effect of extended sensory range via the EyeCane sensory substitution device on the characteristics of visionless virtual navigation. *Multisensory Research*, *27* (5–6), 379–397.
- Makin, T. R., Holmes, N. P., & Ehrsson, H. H. (2008). On the other hand: Dummy hands and peripersonal space. *Behavioural Brain Research*, *191*(1), 1–10.
- McDonald, J. J., Teder-Sälejärvi, W. A., & Ward, L. M. (2001). Multisensory integration and crossmodal attention effects in the human brain. *Science*, *292*(5523), 1791.
- McDonald, J. J., & Ward, L. M. (2000). Involuntary listening aids seeing: Evidence from human electrophysiology. *Psychological Science*, *11*(2), 167–171.
- Merabet, L. B., & Pascual-Leone, A. (2010). Neural reorganization following sensory loss: The opportunity of change. *Nature Reviews Neuroscience*, *11*(1), 44–52. Available from <http://dx.doi.org/10.1038/nrn2758>.
- Meredith, M. A., Nemitz, J. W., & Stein, B. E. (1987). Determinants of multisensory integration in superior colliculus neurons. I. Temporal factors. *The Journal of Neuroscience*, *7*(10), 3215–3229.
- Meredith, M. A., & Stein, B. E. (1983). Interactions among converging sensory inputs in the superior colliculus. *Science*, *221*(4608), 389–391.
- Middlebrooks, J. C., & Green, D. M. (1991). Sound localization by human listeners. *Annual Review of Psychology*, *42*(1), 135–159.
- Millar, S. (1994). *Understanding and representing space: Theory and evidence from studies with blind and sighted children*. Oxford: Oxford University Press, Clarendon Press.
- Millar, S., & Al-Attar, Z. (2004). External and body-centered frames of reference in spatial memory: Evidence from touch. *Perception & Psychophysics*, *66*(1), 51–59.
- Millar, S., & Al-Attar, Z. (2005). What aspects of vision facilitate haptic processing? *Brain and Cognition*, *59*(3), 258–268. Available from <http://dx.doi.org/10.1016/j.bandc.2005.07.005>.
- Miller, J. (1982). Divided attention: Evidence for coactivation with redundant signals. *Cognitive Psychology*, *14*(2), 247–279.
- Miller, J. (1986). Timecourse of coactivation in bimodal divided attention. *Perception & Psychophysics*, *40*(5), 331–343.
- Nijboer, T. C., Kollen, B. J., & Kwakkel, G. (2013). Time course of visuospatial neglect early after stroke: A longitudinal cohort study. *Cortex*, *49*(8), 2021–2027.
- Nijboer, T. C., Kollen, B. J., & Kwakkel, G. (2014). The impact of recovery of visuospatial neglect on motor recovery of the upper paretic limb after stroke. *PLoS One*, *9*(6), e100584.

- Nijboer, T., Van de Port, I., Schepers, V., Post, M., & Visser-Meily, A. (2013). Predicting functional outcome after stroke: The influence of neglect on basic activities in daily living. *Frontier in Human Neuroscience*, 7(182), 1–6. Available from <http://dx.doi.org/10.3389/fnhum.2013.00182>.
- Noel, J. P., Grivaz, P., Marmaroli, P., Lissek, H., Blanke, O., & Serino, A. (2015). Full body action remapping of peripersonal space: The case of walking. *Neuropsychologia*, 70, 375–384.
- Ocelli, V., Spence, C., & Zampini, M. (2011). Audiotactile interactions in front and rear space. *Neuroscience & Biobehavioral Reviews*, 35(3), 589–598.
- Papagno, C., Cecchetto, C., Pisoni, A., & Bolognini, N. (2016). Deaf, blind or deaf-blind: Is touch enhanced? *Experimental Brain Research*, 234(2), 627–636. Available from <http://dx.doi.org/10.1007/s00221-015-4488-1>.
- Pasqualotto, A., & Proulx, M. J. (2012). The role of visual experience for the neural basis of spatial cognition. *Neuroscience Biobehavioral Reviews*, 36(4), 1179–1187. Available from <http://dx.doi.org/10.1016/j.neubiorev.2012.01.008>.
- Passamonti, C., Bertini, C., & Làdavas, E. (2009). Audio-visual stimulation improves oculomotor patterns in patients with hemianopia. *Neuropsychologia*, 47(2), 546–555.
- Pavani, F., & Bottari, D. (2012). Visual abilities in individuals with profound deafness: A critical review. In M. M. Murray, & M. T. Wallace (Eds.), *The neural bases of multi-sensory processes*. Boca Raton, FL: CRC Press/Taylor & Francis.
- Pavani, F., & Röder, B. (2012). Crossmodal plasticity as a consequence of sensory loss: Insights from blindness and deafness. In B. E. Stein (Ed.), *The new handbook of multi-sensory processes* (pp. 737–760). Cambridge, MA: MIT Press.
- Postma, A., Zuidhoek, S., Noordzij, M. L., & Kappers, A. M. (2007). Differences between early-blind, late-blind, and blindfolded-sighted people in haptic spatial-configuration learning and resulting memory traces. *Perception*, 36(8), 1253–1265.
- Previc, F. H. (1998). The neuropsychology of 3-D space. *Psychological Bulletin*, 124(2), 123–164.
- Proulx, M. J., Ptito, M., & Amedi, A. (2014). Multisensory integration, sensory substitution and visual rehabilitation. *Neuroscience and Biobehavioral Reviews*, 41, 1–2.
- Renier, L. A., Anurova, I., De Volder, A. G., Carlson, S., VanMeter, J., & Rauschecker, J. P. (2010). Preserved functional specialization for spatial processing in the middle occipital gyrus of the early blind. *Neuron*, 68(1), 138–148. Available from <http://dx.doi.org/10.1016/j.neuron.2010.09.021>.
- Röder, B., & Rosler, F. (2004). Compensatory plasticity as a consequence of sensory loss. In G. Calvert, C. Spence, & B. E. Stein (Eds.), *The handbook of multisensory processes* (pp. 719–747). Cambridge, MA: MIT Press.
- Sadato, N., Pascual-Leone, A., Grafman, J., Ibanez, V., Deiber, M. P., Dold, G., & Hallett, M. (1996). Activation of the primary visual cortex by Braille reading in blind subjects. *Nature*, 380(6574), 526–528. Available from <http://dx.doi.org/10.1038/380526a0>.
- Sambo, C. F., & Iannetti, G. D. (2013). Better safe than sorry? The safety margin surrounding the body is increased by anxiety. *The Journal of Neuroscience*, 33(35), 14225–14230.
- Sambo, C. F., Vallar, G., Fortis, P., Ronchi, R., Posteraro, L., Forster, B., & Maravita, A. (2011). Visual and spatial modulation of tactile extinction: Behavioural and electrophysiological evidence. *Frontiers in Human Neuroscience*, 6(217). Available from <http://dx.doi.org/10.3389/fnhum.2012.00217>.
- Santangelo, V., & Spence, C. (2007). Multisensory cues capture spatial attention regardless of perceptual load. *Journal of Experimental Psychology: Human Perception and Performance*, 33(6), 1311.

- Santangelo, V., Van der Lubbe, R. H., Belardinelli, M. O., & Postma, A. (2006). Spatial attention triggered by unimodal, crossmodal, and bimodal exogenous cues: A comparison of reflexive orienting mechanisms. *Experimental Brain Research*, *173*(1), 40–48.
- Santangelo, V., Van der Lubbe, R. H., Belardinelli, M. O., & Postma, A. (2008). Multisensory integration affects ERP components elicited by exogenous cues. *Experimental Brain Research*, *185*(2), 269–277.
- Schendel, K., & Robertson, L. C. (2004). Reaching out to see: Arm position can attenuate human visual loss. *Journal of Cognitive Neuroscience*, *16*(6), 935–943.
- Serino, A., Canzoneri, E., & Avenanti, A. (2011). Fronto-parietal areas necessary for a multisensory representation of peripersonal space in humans: An rTMS study. *Journal of Cognitive Neuroscience*, *23*(10), 2956–2967.
- Sharma, A., Nash, A. A., & Dorman, M. (2009). Cortical development, plasticity and reorganization in children with cochlear implants. *Journal of Communication Disorders*, *42*(4), 272–279. Available from <http://dx.doi.org/10.1016/j.jcomdis.2009.03.003>.
- Smith, D. T., Lane, A. R., & Schenk, T. (2008). Arm position does not attenuate visual loss in patients with homonymous field deficits. *Neuropsychologia*, *46*(9), 2320–2325.
- Sparks, D. L., & Nelson, I. S. (1987). Sensory and motor maps in the mammalian superior colliculus. *Trends in Neurosciences*, *10*(8), 312–317.
- Spence, C. (2013). Just how important is spatial coincidence to multisensory integration? Evaluating the spatial rule. *Annals of the New York Academy of Sciences*, *1296*(1), 31–49.
- Spence, C., & Santangelo, V. (2009). Capturing spatial attention with multisensory cues: A review. *Hearing Research*, *258*(1), 134–142.
- Spence, C., & McDonald, J. (2004). The cross-modal consequences of the exogenous spatial orienting of attention. In G. A. Calvert, C. Spence, & B. E. Stein (Eds.), *The handbook of multisensory processes* (pp. 3–26). Cambridge, MA: MIT Press.
- Spence, C., & Driver, J. (Eds.). (2004). *Crossmodal space and crossmodal attention*. Oxford, UK: Oxford University Press.
- Spence, C., & Squire, S. (2003). Multisensory integration: maintaining the perception of synchrony. *Current Biology*, *13*(13), R519–R521.
- Stein, B. E., & Stanford, T. R. (2008). Multisensory integration: Current issues from the perspective of the single neuron. *Nature Reviews Neuroscience*, *9*(4), 255–266.
- Stein, B. E., & Meredith, M. (1990). Multisensory integration. *Annals of the New York Academy of Sciences*, *608*(1), 51–70.
- Stein, B. E., & Meredith, M. A. (1993). *The merging of the senses*. Cambridge, MA: The MIT Press.
- Stevenson, R. A., Fister, J. K., Barnett, Z. P., Nidiffer, A. R., & Wallace, M. T. (2012). Interactions between the spatial and temporal stimulus factors that influence multisensory integration in human performance. *Experimental Brain Research*, *219*(1), 121–137.
- Striem-Amit, E., Ovadia-Caro, S., Caramazza, A., Margulies, D. S., Villringer, A., & Amedi, A. (2015). Functional connectivity of visual cortex in the blind follows retinotopic organization principles. *Brain*, *138*(6), 1679–1695.
- Taffou, M., & Viaud-Delmon, I. (2014). Cynophobic fear adaptively extends peripersonal space. *Frontiers in Psychiatry*, *5*, 122. Available from <http://dx.doi.org/10.3389/fpsy.2014.00122>.
- Ten Brink, A. F., Nijboer, T. C., Bergsma, D. P., Barton, J. J., & Van der Stigchel, S. (2015). Lack of multisensory integration in hemianopia: No influence of visual stimuli on aurally guided saccades to the blind hemifield. *PLoS One*, *10*(4), e0122054.
- Teneggi, C., Canzoneri, E., Di Pellegrino, G., & Serino, A. (2013). Social modulation of peripersonal space boundaries. *Current Biology*, *23*(5), 406–411.

- Theoret, H., Merabet, L., & Pascual-Leone, A. (2004). Behavioral and neuroplastic changes in the blind: Evidence for functionally relevant cross-modal interactions. *Journal of Physiology*, *98*(1–3), 221–233. Available from <http://dx.doi.org/10.1016/j.jphysparis.2004.03.009>.
- Thinus-Blanc, C., & Gaunet, F. (1997). Representation of space in blind persons: Vision as a spatial sense? *Psychological Bulletin*, *121*(1), 20–42.
- Tinga, A. M., Visser-Meily, J. M. A., van der Smagt, M. J., Van der Stigchel, S., van Ee, R., & Nijboer, T. C. W. (2015). Multisensory stimulation to improve low-and higher-level sensory deficits after stroke: A systematic review. *Neuropsychology Review*, *26*(1), 73–91.
- Tinti, C., Adenzato, M., Tamietto, M., & Cornoldi, C. (2006). Visual experience is not necessary for efficient survey spatial cognition: Evidence from blindness. *Quarterly Journal of Experimental Psychology*, *59*(7), 1306–1328. Available from <http://dx.doi.org/10.1080/17470210500214275>.
- Ungar, S., Blades, M., & Spencer, C. (1996). The ability of visually impaired children to locate themselves on a tactile map. *Journal of Visual Impairment & Blindness*, *90*(6), 526–535.
- Urbanski, M., De Schotten, M. T., Rodrigo, S., Oppenheim, C., Touzé, E., Méder, J. F., & Bartolomeo, P. (2011). DTI-MR tractography of white matter damage in stroke patients with neglect. *Experimental Brain Research*, *208*(4), 491–505.
- Van der Lubbe, R. H., Van Mierlo, C. M., & Postma, A. (2010). The involvement of occipital cortex in the early blind in auditory and tactile duration discrimination tasks. *Journal of Cognitive Neuroscience*, *22*(7), 1541–1556.
- Van der Stoep, N., Nijboer, T. C. W., & Van der Stigchel, S. (2014). Exogenous orienting of crossmodal attention in 3-D space: Support for a depth-aware crossmodal attentional system. *Psychonomic Bulletin & Review*, *21*(3), 708–714.
- Van der Stoep, N., Nijboer, T. C. W., Van der Stigchel, S., & Spence, C. (2015). Multisensory interactions in the depth plane in front and rear space: A review. *Neuropsychologia*, *70*, 335–349.
- Van der Stoep, N., Serino, A., Farnè, A., Di Luca, M., & Spence, C. (2016). Depth: The forgotten dimension in multisensory research. *Multisensory Research*. Available from <http://dx.doi.org/10.1163/22134808-00002525>.
- Van der Stoep, N., Spence, C., Nijboer, T. C. W., & Van der Stigchel, S. (2015). On the relative contributions of multisensory integration and crossmodal exogenous spatial attention to multisensory response enhancement. *Acta Psychologica*, *162*, 20–28.
- Van der Stoep, N., Van der Stigchel, S., Nijboer, T. C. W., & Van der Smagt, M. J. (2015). Audiovisual integration in near and far space: effects of changes in distance and stimulus effectiveness. *Experimental Brain Research*, *234*(5), 1175–1188.
- Van der Stoep, N., Visser-Meily, J. M., Kappelle, L. J., de Kort, P. L., Huisman, K. D., Eijsackers, A. L., & Nijboer, T. C. (2013). Exploring near and far regions of space: distance-specific visuospatial neglect after stroke. *Journal of Clinical and Experimental Neuropsychology*, *35*(8), 799–811.
- van Dijk, R., Kappers, A. M., & Postma, A. (2013a). Haptic spatial configuration learning in deaf and hearing individuals. *PLoS One*, *8*(4), e61336. Available from <http://dx.doi.org/10.1371/journal.pone.0061336>.
- van Dijk, R., Kappers, A. M., & Postma, A. (2013b). Superior spatial touch: Improved haptic orientation processing in deaf individuals. *Experimental Brain Research*, *230*(3), 283–289. Available from <http://dx.doi.org/10.1007/s00221-013-3653-7>.
- Van Dijk, R., Nelson, C., Postma, A., & Van Dijk, J. (2010). Deaf children with severe multiple disabilities: Etiologies, intervention, and assessment. In M. Marschark, & P. E. Spencer (Eds.), *The Oxford handbook of deaf studies, language, and education volume 2* (Vol. 2) Oxford: Oxford University Press.

- Vroomen, J., & Keetels, M. (2010). Perception of intersensory synchrony: A tutorial review. *Attention, Perception, & Psychophysics*, 72(4), 871–884.
- Welch, R. B., DuttonHurt, L. D., & Warren, D. H. (1986). Contributions of audition and vision to temporal rate perception. *Perception & Psychophysics*, 39(4), 294–300.
- Welch, R. B., & Warren, D. H. (1980). Immediate perceptual response to intersensory discrepancy. *Psychological Bulletin*, 88(3), 638.
- Wong, M., Gnanakumaran, V., & Goldreich, D. (2011). Tactile spatial acuity enhancement in blindness: Evidence for experience-dependent mechanisms. *Journal of Neuroscience*, 31(19), 7028–7037. Available from <http://dx.doi.org/10.1523/JNEUROSCI.6461-10.2011>.
- Zwiers, M. P., Van Opstal, A. J., & Cruysberg, J. R. (2001). A spatial hearing deficit in early-blind humans. *Journal of Neuroscience*, 21(9), 141–145, RC142.

FURTHER READING

- Làdavas, E., Di Pellegrino, G., Farnè, A., & Zeloni, G. (1998). Neuropsychological evidence of an integrated visuotactile representation of peripersonal space in humans. *Journal of Cognitive Neuroscience*, 10(5), 581–589.
- Meredith, M. A., & Stein, B. E. (1986). Visual, auditory, and somatosensory convergence on cells in superior colliculus results in multisensory integration. *Journal of Neurophysiology*, 56(3), 640–662.
- Nidiffer, A. R., Stevenson, R. A., Fister, J. K., Barnett, Z. P., & Wallace, M. T. (2016). Interactions between space and effectiveness in human multisensory performance. *Neuropsychologia*. Available from <http://dx.doi.org/10.1016/j.neuropsychologia.2016.01.031>.
- Rizzolatti, G., Fadiga, L., Fogassi, L., & Gallese, V. (1997). The space around us. *Science*, 277(5323), 190.
- Ross, L. A., Saint-Amour, D., Leavitt, V. M., Javitt, D. C., & Foxe, J. J. (2007). Do you see what I am saying? Exploring visual enhancement of speech comprehension in noisy environments. *Cerebral Cortex*, 17(5), 1147–1153.
- Stevenson, R. A., & James, T. W. (2009). Audiovisual integration in human superior temporal sulcus: Inverse effectiveness and the neural processing of speech and object recognition. *Neuroimage*, 44(3), 1210–1223.
- Van Atteveldt, N. M., Formisano, E., Blomert, L., & Goebel, R. (2007). The effect of temporal asynchrony on the multisensory integration of letters and speech sounds. *Cerebral Cortex*, 17(4), 962–974.