22 Visual Abilities in Individuals with Profound Deafness: A Critical Review

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22.1 VISUAL ABILITIES IN PROFOUND DEAFNESS: AN OPEN CHALLENGE FOR CROSS-MODAL PLASTICITY RESEARCH

The world is inherently multisensory, and our ability to interact with it largely depends on the capability of our cognitive system to coherently use and integrate such variety of sensory inputs. Consider, for instance, the way in which we monitor the environment. In humans, vision plays a crucial role in informing the cognitive system about the spatial layout of the scene, and in recognizing objects and events. However, during steady fixation of gaze in one direction, the visual field typically extends 100° laterally on either side, 60° upward, and 75° downward (Harrington 1971). This leaves a large portion of the surrounding environment unexplored to vision, unless constant eye, head, and trunk movements are performed. Other distal senses, such as hearing or smell, can overcome this visual field limitation, providing inputs about regions of the environment beyond the boundaries of current visual perception. These additional sensory modalities can inform our cognitive system about stimuli that occur behind our body, are hidden by visual obstacles, or occur very far in space. In particular, hearing can provide a good estimate of the most likely location in space of the nonvisible stimulus (see Heffner and Heffner 1992 for a cross-species evaluation of the relationship between the ability to localize a sound and the width of the field of best vision). In addition, hearing constantly models the acoustic regularity in the environment and reacts to violations of such regularity, regardless of the current behavioral goal of the individual (Näätänen 1992). Thus, audition constitutes a fundamental guidance for reorienting our exploratory behavior. Efficient integration of sensory inputs from audition and vision is therefore essential for successful exploration of the surrounding environment.

The way our cognitive system perceives the multisensory environment in which we live leads to a fundamental question that has long been debated among scientists and philosophers: What are the consequences of the absence of one sensory modality for cognition and multisensory perception? For instance, which are the consequences of long-term auditory deprivation due to profound deafness for the remaining sensory modalities, mainly vision and touch? An interest for this issue can be traced back at least to the seventeenth century (for historical reviews, see Hartmann 1933; Jordan 1961), and two opposing hypotheses have traditionally been put forward to account for the impact of sensory deprivation (i.e., deafness or blindness) on the remaining senses. The first hypothesis is that a substantial deficit in one sensory modality could affect the development and organization of the other sensory systems. We will refer to this first perspective as the *perceptual deficit hypothesis.* When applied to the case of profound deafness, the perceptual deficit hypothesis predicts poorer visual and tactile perceptual performance in deaf individuals, as compared to the age-matched hearing controls (e.g., Myklebust 1964). This hypothesis was based on the assumption that auditory deficiency can have a direct impact on the development of the other senses. In addition, it assumed that any language impairments resulting from profound deafness would limit hearing-impaired children in their interaction with the world, and result in a cognitive development lag in perceptual and cognitive tasks (Furth 1966). The second hypothesis is that a deficit in one sensory system would make the other modalities more sensitive, vicariously compensating for the loss of one sensory channel (e.g., Gibson 1969). We will refer to this second perspective as the *sensory compensation hypothesis.* When applied to the case of profound deafness, the sensory compensation hypothesis predicts that the visual and tactile modalities will show enhanced sensitivity. The latter prediction is often stated both in terms of behavioral consequences of deafness, and in terms of its neural outcomes. Specifically, the neural implications of the sensory compensation hypothesis are that the brain areas serving the impaired sensory modality may develop the ability to process perceptual inputs from one or more of the intact sensory systems (*functional reallocation account*), or alternatively that brain areas of the remaining senses may acquire enhanced functional and processing capabilities (*remaining senses hypertrophy account*).

After more than 30 years of systematic research conducted mainly on the visual abilities of profoundly deaf individuals, it is apparent that the long-standing debate as to whether perceptual and cognitive functions of deaf individuals are deficient or supranormal is far from being settled. Several reviews of this literature (e.g., Parasnis 1983; Bavelier et al. 2006; Mitchell and Maslin 2007) clearly indicate that deaf and hearing individuals perform comparably on a number of perceptual tasks. As we shall see later (see Section 22.2.1), this conclusion is strongly supported by tasks involving basic perceptual thresholds. Instead, other studies have revealed a differential performance in the two groups, either in the direction of deficient abilities in deaf than hearing participants (e.g., Quittner et al. 2004; Parasnis et al. 2003), or in the direction of supranormal abilities for the deaf population (e.g., Bottari et al. 2010; Loke and Song 1991; Neville and Lawson 1987). In this context, it should perhaps be emphasized that in the absence of clear behavioral differences between deaf and hearing participants, even the most striking differences between the two groups observed at the neural level cannot disentangle between the perceptual deficit hypothesis and the sensory compensation hypotheses. For instance, much of the renewed interest in the study of visual abilities in deaf individuals has been motivated by the seminal work of Neville et al. (1983). In that study, visual evoked potentials (VEPs) recorded from the scalp of eight congenitally deaf adults were significantly larger over both auditory and visual cortices, with respect to those of eight hearing controls, specifically for visual stimuli occurring in the periphery of the visual field (8.3°). Although this pioneering work implies that the lack of auditory experience from an early age can influence the organization of the human brain for visual processing [a finding that was later confirmed and extended by many other studies using different methodologies for the recording of brain responses; e.g., electroencephalogram (EEG): Neville and Lawson 1987; magnetoencephalography: Finney et al. 2003; functional magnetic resonance imaging: Bavelier et al. 2000, 2001], in the absence of a behavioral difference between the two groups it remains potentially ambiguous whether modifications at the neural level are an index of deficiency or compensation. In other words, even if one assumes that larger visual evoked components (e.g., Neville et al. 1983; Neville and Lawson 1987) or stronger bold responses (e.g., Bavelier et al. 2000; 2001) indicate enhanced processing of the incoming input, if this is not accompanied by behavioral enhancement it is difficult to conclude that it really serves some adaptive functional role. Unfortunately, the current evidence in the literature lacks this explicative power. With the only exception of the work by Neville and Lawson (1987), all other neuroimaging studies focused on measures of brain response alone, instead of combined measures of brain response and behavior. Furthermore, conclusive evidence that cortical reorganization serves a functional role can only originate from the observation that interfering with the reorganized brain response [e.g., using transcranial magnetic stimulation (TMS)] impairs the supranormal behavioral performance in the sensory-deprived participants (e.g., see Cohen et al. 1997 for an example of abolished supranormal tactile discrimination in the blind, following disruption of occipital lobe function using TMS).

22.1.1 MULTIPLE OPERATIONAL DEFINITIONS

The solution of the controversy between deficient or compensatory behavioral outcomes of profound deafness should first of all rely on a clear operational definition of the concept of "enhanced visual abilities in deaf individuals." On one hand, the question "Do deaf individuals see better?" (e.g., Rettenbach et al. 1999; Bavelier et al. 2006) is provocatively broad and calls for a specification of the domains of visual perception in which the sensory compensation hypothesis is to be tested for the case of deafness. On the other hand, a definition centered on the sole concept of enhanced *sensitivity* (e.g., Bross 1979a) is perhaps too limited, as it implies that the compensation hypothesis can only be true whenever discrimination sensitivity of deaf individuals is better than that measured in age-matched hearing controls. The concept of sensitivity refers to the ability of a perceptual system to discriminate a signal (e.g., a target) from noise (e.g., background events), and it is best described within the theoretical framework of the Signal Detection Theory (SDT; Green and Swets 1966). In particular, SDT allows distinguishing sensitivity (expressed by the d' index) from the observer's response criterion (expressed by the c or *ol* β indices). Although the SDT is largely considered a standpoint for the study of perception, it is worth noting that the studies on visual abilities in deaf individuals have very rarely used the SDT approach to describe performance (see Bross 1979a, 1997b; Neville and Lawson 1987; Bosworth and Dobkins 1999, 2002a, 2002b; Bottari et al., in preparation).

"Bosworth and Dobkins 2002b" has no corresponding entry in the Reference list; please provide the necessary details for this citation.

The first aim of this review is to provide a detailed description of the empirical evidence of visual abilities in profound deafness, structured as a function of the visual tasks that have been adopted by the different investigators and the dependent variable considered in the analyses. We start by describing the studies that investigated *perceptual thresholds* in the visual and tactile modalities, which gave an operational definition of enhanced visual ability in terms of better low-level sensitivity to the stimulus. Second, we describe studies that centered on *simple detection or lateralization* (left/right) responses, which gave an operational definition of enhanced visual ability in terms of faster response to a target onset. Third, we review studies that adopted *visual search* tasks, which gave on operational definition in term of efficiency in searching for a target feature in the visual scene. Fourth, we review reports that centered on *discrimination and identification* of suprathreshold stimuli, which gave an operational definition of enhanced ability in terms of better recognition of perceptual events. Finally, we conclude with a section on visual tasks of higher complexity that extended the operational definition to include the contribution of visual working memory and dual task performance.

22.1.2 Making Sense of Heterogeneity

In addition to the controversy between “deficit” and “compensation” accounts, another critical issue in this research domain concerns the understanding of which aspect may be transversal to the different behavioral tasks, and may possibly explain the heterogeneity of the empirical results.

The first transversal aspect that may account for the heterogeneity of the results is the diversity in the deaf sample characteristics. As originally pointed out by Hoemann (1978), in choosing deaf participants several studies have not controlled for differences in the amount of hearing loss, etiology of deafness, time from deafness onset at testing, and language(s) or mode(s) of communication used by deaf participants (see also Parasnis 1983). Recently, Bavelier and colleagues (2006) suggested that these differences in the deaf population sample can largely account for the heterogeneity in the literature. Specifically, they argued that studies reporting deficient visual functions in deaf than hearing individuals typically included deaf participants with heterogeneous background, whereas studies that have documented enhanced visual functions only included “deaf native signers” (i.e., individuals with no associated central nervous system damage and born profoundly deaf to deaf parents; Bavelier et al. 2006, p. 512). This specific deaf group achieves language development milestones at the same rate and time as hearing individuals, thus giving the opportunity to investigate the effects of auditory deprivation at the net of other confounding factors, such as language deprivation or atypical cognitive development due to communication deficiencies. As we shall see later (see Section 22.3.2), although a selection of deaf participants on the basis of the criteria proposed by Bavelier et al. (2006) has great methodological benefits, it appears unlikely that the heterogeneity in the empirical evidence can be reduced to this aspect alone. Furthermore, restricting the analysis only to “deaf native signers” would greatly limit generalization of the results, as this subgroup represents only 5% of the total deaf population (at least in the United States; see Mitchell and Karchmer 2002).

The second important aspect that has often been emphasized as potential source of heterogeneity in the empirical evidence is the *visual characteristics* of the target stimulus. Several authors (e.g., Armstrong et al. 2002; Bavelier et al. 2006; Neville and Bavelier 2002) have proposed that enhanced visual abilities in deaf individuals may emerge selectively for the analysis of visual features that are preferentially processed within the visual-for-action pathway (also termed “motion pathway”), associated with the dorsal visual stream (Milner and Goodale 1995). For instance, an event-related potential (ERP) study by Armstrong and colleagues (2002) revealed enhanced cortical responses (larger N1 components) in deaf than in hearing adults in response to task-irrelevant motion stimuli at peripheral locations. Importantly, when cortical activity was compared between groups for stimuli varying along the color dimension (a visual feature preferentially processed by the ventral visual stream), enhanced cortical responses for deaf than hearing participants were no longer evident. Motion stimuli have also been shown to activate the MT+ complex more strongly in deaf than in hearing individuals using functional neuroimaging (Bavelier et al. 2000, 2001), and to activate the right auditory cortex in the deaf participants (Fine et al. 2005; Finney et al. 2001).

The third aspect that has systematically been described as critical for enhanced visual abilities in deaf people is the eccentricity of the visual stimulus. The main working hypothesis for several investigations in this field has been that any visual enhancement in deaf individuals should emerge particularly for visual stimuli appearing toward the periphery of the visual field (e.g., Parasnis 1983; Neville and Lawson 1987). This prediction stems from the observation that, under normal conditions, the auditory system provides important information about the events that occur outside the field of view. Therefore, in the absence of audition, visual processing might recalibrate to favor visual events outside the fovea, in the attempt to monitor the environment through peripheral vision (e.g., Loke and Song 1991; Parasnis and Samar 1985). As shall be shown, a number of independent studies have provided general support to the hypothesis that peripheral regions of the visual field have a different status for deaf individuals with respect to hearing controls. However, the actual visual eccentricities associated with the terms "central," "perifoveal," and "peripheral" considerably varied across the different studies. Researchers have referred to stimulus location as "central" both when the stimulus was presented directly at fixation (e.g., Poizner and Tallal 1987) and when it was perifoveal (e.g., Neville and Lawson 1987). More critically, the term "peripheral" has been applied to locations in the visual field ranging from 3° of eccentricity (e.g., Chen et al. 2006) to 20° or more (e.g., Colmenero et al. 2004; Loke and Song 1991; Stevens and Neville 2006). As pointed out by Reynolds (1993), this ambiguity in the adopted terminology originate from the fact that the boundaries of the foveal region (up to 1.5° from fixation) are well defined by anatomical structures, whereas the distinction between perifoveal and peripheral visual field is not.

Finally, most researchers have suggested that spatial selective attention plays a key role in modulating visual responses in deaf individuals (e.g., Bavelier et al. 2006; Dye et al. 2008; Loke and Song 1991; Neville and Lawson 1987; Parasnis and Samar 1985; Sladen et al. 2005). This suggestion originated from the studies that examined attention orienting in deaf and hearing participants (e.g., Colmenero et al. 2004; Parasnis and Samar 1985) and found that deaf individuals pay less of a cost when detecting a target occurring at invalidly cued locations. Furthermore, a potential difference in selective attention has been proposed by those studies that examined the interference of flankers on target discrimination (Proksch and Bavelier 2002; Sladen et al. 2005) and found that deaf individuals were more susceptible to peripheral flankers than hearing controls. Finally, the suggestion that employment of selective attention resources is the key requisite for revealing differences between deaf and hearing participants has emerged from the empirical observation that differences between deaf individuals and hearing controls have sometimes emerged specifically when attention was endogenously directed to the target (e.g., Bavelier et al. 2000; Neville and Lawson 1987; but see Bottari et al. 2008).

However, whether *all* aspects of visual enhancement in deaf individuals are necessarily linked to allocation of selective attention in space is still a matter of debate. Furthermore, it is well acknowledged that selective spatial attention is not a unitary mechanism, and at least two functionally and anatomically distinct mechanisms of spatial attention have been identified (Corbetta and Shulman 2002; Jonides 1981; Mayer et al. 2004; Posner 1980). Visual attention can be oriented to an object or a location in a bottom-up fashion, because an abrupt change in visual luminance at the retinal level has occurred in a specific region of the visual field. This type of attention orienting is entirely automatic and has typically been referred to as *exogenous* orienting. Alternatively, visual attention can be summoned to an object or a location because of its relevance for the behavioral goal of the individual. This type of top-down attention orienting is voluntary and strategic, and has typically been referred to as *endogenous* orienting. Whether one or both of the components of selective attention are changed as a consequence of deafness remains an open question. Thus, whenever the claim that "early deafness results in a redistribution of attentional resources to the periphery" is made (e.g., Dye et al. 2008, p. 75), one should also ask which aspect of selective attention (endogenous, exogenous, or both) is changed by profound deafness.

In sum, four distinct transversal aspects may contribute to explain the heterogeneity of the empirical results in the different behavioral tasks: diversity in the deaf sample characteristics, visual characteristics of the target stimulus, target eccentricity, and role of selective spatial attention. The second aim of the present review is to reevaluate the empirical evidence in support of these four different (but possibly interrelated) aspects in modulating visual abilities in deaf individuals.

22.2 A TASK-ORIENTED REVIEW OF EMPIRICAL EVIDENCE

22.2.1 Perceptual Thresholds Tasks

One of the first studies to investigate perceptual thresholds in deaf individuals was conducted by Bross (1979a), who tested *brightness discrimination* sensitivity in six deaf and six hearing children

(11 years old on average) for two circular patches of white light presented at 4.8° of eccentricity, on opposite sides with respect to the participant's body midline. Initially, the just noticeable difference (JND) between the two patches was measured for each participant. Then, brightness for one of the two stimuli (variable) was set to 0.75 JND units above or equal to the other (standard), and participants were instructed to indicate whether the variable stimulus was brighter or equal in apparent brightness with respect to the standard. In the latter task, the probability that the variable stimulus was brighter than the standard changed between blocks, from less likely (0.25), to equal (0.50), to more likely (0.75). Deaf and hearing participants showed comparable JNDs for brightness discrimination. However, their sensitivity in the forced-choice task was better than hearing controls, as measured by d'. Intriguingly, deaf performance was entirely unaffected by the probability manipulation (i.e., deaf participants maintained a stable criterion, as measured by β), unlike hearing controls who became more liberal in their criterion as stimulus probability increased. However, the same two groups of participants showed comparable sensitivity (d') when retested in a second study with largely comparable methods (Bross 1979b). In addition, in one further study adapting the same paradigm for *visual-flicker thresholds*, no difference between deaf and hearing controls emerged it terms or d' or β (Bross and Sauerwein 1980). This led Bross and colleagues (Bross 1979a, 1997b; Bross and Sauerwein 1980) to conclude that no enhanced sensory sensitivity is observed in deaf children, in disagreement with the sensory compensation hypothesis.

Finney and Dobkins (2001) reached a similar conclusion when measuring *contrast sensitivity* to moving stimuli in 13 congenital or early deaf adult participants (all signers), 14 hearing subjects with no signing experience, and 7 hearing subjects who signed from birth [Hearing Offspring of Deaf parents (HOD)]. Stimuli were black and white moving sinusoidal gratings presented for 300 ms to the left or to the right of one visual marker, and the participant's task was to report whether the stimulus appeared to the left or to the right of the marker. Five markers were visible throughout the task (the central fixation cross and four dots located at 15° of eccentricity with respect to fixation). The stimulus could appear next to any of the five markers, thus forcing participants to distribute their visual attention across several visual locations. The luminance contrast required to yield 75% correct performance was measured for each participant across a range of 15 different combinations of spatial and temporal frequency of the stimulus. Regardless of all these manipulations, deaf, hearing, and HOD participants performed comparably on both central and peripheral stimuli, leading to the conclusion that neither deafness nor sign-language use lead to overall increases or decreases in absolute contrast sensitivity (Finney and Dobkins 2001, p. 175). Stevens and Neville (2006) expanded this finding by showing that contrast sensitivity was comparable in 17 congenital deaf and 17 hearing individuals, even for stimuli delivered in the macula of the participant, at 2° around visual fixation (see also Bavelier et al. 2000, 2001, for further evidence of comparable luminance change detection in deaf and hearing individuals). Interestingly, a between-group difference was instead documented when the task was changed to unspeeded detection of a small (1 mm) white light, moving from the periphery to the center of the visual field. In this kinetic perimetry task, deaf participants showed an enlarged field of view (about 196 cm^2) with respect to hearing controls (180 cm^2), regardless of stimulus brightness.

The latter finding suggests that perceptual thresholds may differ for deaf and hearing individuals when motion stimuli are employed. However, three further investigations (Bosworth and Dobkins 1999, 2002a; Brozinsky and Bavelier 2004) that examined the performance of deaf and hearing participants in *motion discrimination* tasks indicate that this is not always the case. Bosworth and Dobkins (1999) tested 9 congenital or early deaf (all signers) and 15 hearing (nonsigner) adults in a motion direction–discrimination task. The stimulus consisted of a field of white dots presented within a circular aperture, in which a proportion of dots (i.e., signal dots) moved in a coherent direction (either left or right), whereas the remaining dots (i.e., noise dots) moved in a random fashion. Similar to the study of Finney and Dobkins (2001), stimuli were either presented at central fixation, or 15° to the left or to the right of fixation. Participants were instructed to report the direction of motion with a key press, and the proportion of coherent motion signal yielding 75% correct performance was measured for each participant. Mean thresholds did not differ between deaf and hearing controls, regardless of stimulus eccentricity (central or peripheral), stimulus duration (250, 400, or 600 ms) and vertical location of the lateralized stimuli (upper or lower visual field). The only between group difference concerned the performance across the two visual hemifields. Deaf participants exhibited a right visual field (RVF) advantage, whereas hearing controls exhibited a slight left visual field (LVF) advantage. The latter finding, however, reflected the signing experience rather than auditory deprivation, and resulted from the temporal coincidence between visual and linguistic input in the left hemisphere of experienced signers, as subsequently shown by the same authors (Bosworth and Dobkins 2002b). A convergent pattern of result emerged from the study by Bosworth and Dobkins (2002a), in which 16 deaf signers (12 congenital), 10 hearing signers, and 15 hearing controls were asked to detect, within a circular aperture, the direction of motion of a proportion of dots moving coherently (leftward or rightward), whereas the remaining dots moved in a random fashion. The proportion of dots moving coherently varied across trials, to obtain a threshold of the number of moving coherently dots necessary to yield the 75% of correct discriminations. The results showed that all group of participants performed comparably in terms of thresholds suggesting that deafness does not modulate the motion threshold.

Convergent findings also emerged from a study by Brozinsky and Bavelier (2004), in which 13 congenitally deaf (signers) and 13 hearing (nonsigner) adults were asked to detect velocity increases in a ring of radially moving dots. On each trial, dots accelerated in one quadrant and participants indicated the location of this velocity change in a four-alternative forced choice. Across experiments, the field of dots extended between 0.5° and 8°, or between 0.4° and 2° (central field), or between 12° and 15° (peripheral field). The temporal duration of the velocity change yielding to 79% correct was measured for each participant. Regardless of whether the dots moved centrally or peripherally, velocity thresholds were equivalent for deaf and hearing individuals. Similar to the study by Bosworth and Dobkins (1999), deaf signers displayed better performance in the RVF than the LVF, again as a possible result of their fluency in sign language.

Equivalent performance in deaf and hearing individuals has been documented also when assessing *temporal perceptual thresholds* (e.g., Bross and Sauerwein 1980; Poizner and Tallal 1987; Nava et al. 2008; but see Heming and Brown 2005). Poizner and Tallal (1987) conducted a series of experiments to test temporal processing abilities in 10 congenitally deaf and 12 hearing adults. Two experiments examined flicker fusion thresholds for a single circle flickering on and off at different frequencies, or for two circles presented in sequence with variable interstimulus interval (ISI) (Poizner and Tallal 1987; Experiments 1 and 2). One additional experiment tested temporal order judgment abilities for pairs or triplets of visual targets presented in sequence (Poizner and Tallal 1987; Experiment 3). All visual targets appeared from the same central spatial location on the computer screen and participants were asked to report the correct order of target appearance. No difference between deaf and hearing participants emerged across these tasks. More recently, Nava et al. (2008) tested 10 congenital or early deaf adults (all signers), 10 hearing controls auditory-deprived during testing, and 12 hearing controls who were not subjected to any deprivation procedure, in a temporal order judgment for pairs of visual stimuli presented at perifoveal (3°) or peripheral (8°) visual eccentricities. Regardless of stimulus eccentricity, temporal order thresholds (i.e., JNDs) and points of subjective simultaneity did not differ between groups. Notably, however, faster discrimination responses were systematically observed in deaf than hearing participants, especially when the first of the two stimuli appeared at peripheral locations (Nava et al. 2008).

Finally, one study testing perceptual threshold for frequency discrimination in the tactile modality also confirmed the conclusion of comparable perceptual thresholds in deaf and hearing individuals (Levanen and Hamdorf 2001). Six congenitally deaf (all signers) and six hearing (nonsigners) adults were asked to decide whether the frequency difference between a reference stimulus (at 200 Hz) and a test stimulus (changing in interval between 160 and 250 Hz) was “rising” or “falling.” The frequency difference between the two stimuli that yielded 75% correct responses was measured for each participant. Although the frequency difference threshold was numerically smaller for deaf than hearing participants, no statistically significant difference emerged.

In sum, the studies that have adopted perceptual thresholds to investigate the consequences of deafness on vision and touch (i.e., used an operational definition of better performance in terms of better low-level sensitivity to the stimulus) overall documented an entirely comparable performance between deaf and hearing individuals. Importantly, these findings emerged regardless of whether hearing-impaired participants were congenitally deaf born from deaf parents or early deaf. One clear example of this is the comparison between the study by Poizner and Tallal (1987) and Nava et al. (2008), which tested genetically versus early deaf on a comparable temporal order judgment task, and converged to the same conclusion. The absence of a difference at the perceptual level also emerged regardless of stimulus feature and eccentricity, i.e., regardless of whether target stimuli were static (e.g., Bross 1979a, 1979b) or moving (e.g., Bosworth and Dobkins 1999; Brozinsky and Bavelier 2004), and regardless of whether they appeared at central (e.g., Bosworth and Dobkins 1999; Brozinsky and Bavelier 2004; Poizner and Tallal 1987; Stevens and Neville 2006) or peripheral locations (e.g., Bosworth and Dobkins 1999; Brozinsky and Bavelier 2004; Nava et al. 2008). Finally, making the stimulus location entirely predictable (Bross 1979a; Poizner and Tallal 1987) or entirely unpredictable (e.g., Bosworth and Dobkins 1999; Brozinsky and Bavelier 2004) also had no effect, indicating that comparable performance of deaf and hearing participants was not modulated by the direction of selective visual attention in the scene. The only notable discrepancy with respect to this very consistent pattern of results is the observation of Stevens and Neville (2006) that deaf individuals possess a larger field of view with respect to hearing controls in the kinetic perimetry task. It would be interesting to examine whether this finding can also be replicated with stationary target at the extreme visual periphery.

22.2.2 Simple Detection and Lateralization Tasks

Another approach to the study of visual abilities in profound deafness has been the direct assessment of the reactivity of deaf individuals in response to simple visual events or the assessment of their lateralization abilities (left vs. right response). One important aspect to note concerning this seemingly simple tasks, is that any advantage measured using these procedures could reflect faster processing of the perceptual events, faster response preparation or release, or a combination of the two. Many of the early studies on visual abilities in deaf individuals that aimed to test visual speed (e.g., the classic article by Doehring and Rosenstein 1969, entitled “Speed of visual perception in deaf children”; see also Olson 1967; Hartung 1970) actually examined unspeeded discriminations and visual memory abilities for stimuli presented tachistoscopically. Thus, they are not directly informative about the speed of visual processing and the speed of response in deaf people.

Loke and Song (1991) were among the first to compared 20 congenital or early-deaf high school students and 19 hearing controls, in a task requiring simple detection of an asterisk briefly appearing on the computer screen. The asterisk was presented either at fixation (0.5°), or in the visual periphery (25°), and the task was always performed in monocular vision. The results documented faster responses for deaf than hearing controls (85 ms on average), selectively for targets appearing at peripheral locations. Interestingly, a similar between-group difference was also numerically evident for central locations (38 ms), and perhaps fell short of significance because of the very limited number of trials in each experimental condition (20 trials overall, 10 for each target location).

Two years later, Reynolds (1993) also examined a group of 16 adult participants with early deafness (before 3 years of age, all signers) and 16 hearing controls, in two speeded detection tasks to visual stimuli presented using a tachistoscope. In one task (baseline measure; Reynolds 1993, p. 531), simple detection RTs were recorded in response to a black circular target, presented for 70 ms directly at fixation, in the absence of any peripheral stimulus. In the other task, participants were required to make a speeded bilateral key press to indicate the side of a perifoveal target (4°), by pressing a button located to the left or to the right of the starting position of the responding finger

Please define RT and introduce the abbreviation at first occurrence.

(the purpose of the simultaneous bilateral response was to balance hemispheric motoric activity in the task). Perifoveal targets consisted of six simple shapes (e.g., circle, square, triangle, diamond) that could be presented alone or simultaneously with task-irrelevant shapes of increasing complexity (from basic shapes to human faces or letters) delivered at fixation. Immediately after stimulus detection, participants were also required to identify the shape of the peripheral stimulus. Two results are noteworthy: first, simple detection of the foveal circle (baseline task) was faster for deaf than hearing participants (70 ms on average); second, simple detection and subsequent discrimination of the peripheral shapes also confirmed faster RTs for deaf than hearing participants (56 ms), but failed to show any between-group difference in identification accuracy (see Section 22.2.4 for further discussion of this study).

More recently, Bottari et al. (in preparation) asked 11 congenital or early deaf (all signers) and 11 hearing adults (non signers) to press the space bar of the computer keyboard to the appearance of a small black circle, delivered for 48 ms on the computer screen at 3° or 8° of eccentricity. The results showed that deaf were faster than hearing controls (56 ms on average) at detecting the onset of the visual target, regardless of whether it appeared at 3° or 8°. Similarly, Bottari et al. (2010) asked a different group of 11 congenital or early deaf (all signers) and 11 hearing controls (non signers) to detect a circle open on the left or right side, presented for 48 ms at the 3° or 8° from central fixation. Stimuli were now corrected in size as a function of their eccentricity, and trials per condition were increased from 24 to 96 to increase statistical power. The results of this second study entirely supported those of Bottari et al. (in preparation), and showed a response time advantage in deaf than hearing participants (44 ms on average) that again was not spatially selective, i.e., it emerged regardless of target location instead of appearing only for peripheral targets (Loke and Song 1991). One further finding of the study by Bottari and colleagues (2010) was that the overall RT advantage for deaf participants emerged together with a differential response time ratios in the two groups as a function of target location. Hearing controls paid a significant RT cost when responding to peripheral than central target, whereas deaf individuals performed comparably across the two target locations. This suggests that advantages in reactivity and advantages in peripheral processing may be two dissociable aspects of enhanced visual processing in deaf individuals (see Section 22.3.3 for further discussion of this point).

Other studies measuring speeded simple detection or speeded target lateralization in deaf people also manipulated the direction of attention before target onset, typically adapting the cue–target paradigm developed by Posner (1980). The first study to adopt this manipulation was conducted by Parasnis and Samar in 1985. They tested 20 hearing and 20 congenitally deaf college students (all signers and born from deaf parents) in a task requiring a speeded bimanual response (see Reynolds 1993) to indicate the side of a black unfilled circle, presented for 100 ms at 2.2° from central fixation. The stimulus was preceded by an arrow indicating the correct target side 80% of the times, or by a neutral cross signaling equal probability of the target on either side. In addition, across blocks, the peripheral target was presented with concurrent stimulation at fixation (five black crosses; i.e., foveal load condition) or alone (no load condition). Unlike the simple detection studies described above, the results of this experiment showed no overall RT advantage for deaf than hearing participants (in fact, there was even a trend for slower RTs in deaf than participants overall). Furthermore, all participants showed RT benefits and costs, with respect to the neutral trials, when the target appeared at the cued or the uncued location, respectively. However, deaf participants paid less cost than hearing controls when responding to targets at the *uncued* locations under the foveal load condition. Parasnis and Samar (1985) interpreted this finding as evidence of more efficient "redirecting of attention from one part of the visual field to another in the presence of interfering foveal stimulation," and concluded that "developmental experience involving a visual–spatial language and/or a predominantly visual (as contrasted with visual plus auditory) perception of the world leads to selective and ecologically useful alterations in attentional control of perceptual processes" (Parasnis and Samar 1985, p. 321).

The results and conclusions of the classic study by Parasnis and Samar (1985) created the basis for the widespread notion that attention reorienting is more efficient in deaf than hearing individuals.

However, two further contributions that also examined simple detection of visual stimuli in the presence of attentional cues suggest a more complex framework. Colmenero et al. (2004) asked 17 deaf (all signers with prelingually deafness) and 27 hearing adults to press a key whenever an "O" appeared on the computer screen. The target appeared for 150 ms, at 20° of eccentricity to the left or the right of central fixation, and was preceded by a vertical mark delivered at the exact target location (valid condition, 53% of the trials), on the opposite side with respect to the target (invalid condition, 13% of the trials) or on both sides (neutral condition, 33% of the trials). Stimulus onset asynchrony (SOA) between cue and target ranged between 125 and 250 ms. Note that the use of peripheral *informative* cues in this paradigm inevitably mixed exogenous and endogenous cueing of attention within the same task. Deaf participants were faster than hearing control at detecting the target (43 ms on average). Furthermore, the analysis of RT costs and benefits, for invalid and valid cues, respectively, revealed that both attentional effects were larger in hearing than deaf participants. In a second experiment, Colmenero and colleagues (2004) examined whether performance in the two groups differed when the SOA between the lateralized cue and the target was extended to 350 or 850 ms. With such long SOAs, hearing individuals typically show a cost at detecting targets occurring at the cued location, which is interpreted as inhibition to reexplore locations where attention has been previously oriented [i.e., inhibition of return (IOR); Klein 2000)]. The results of this second experiment revealed less enduring IOR in deaf than in hearing participants, again suggesting a different role of attention orienting in the hearing-deprived population.

Chen et al. (2006) asked 16 congenitally deaf and 22 hearing adults to detect the occasional appearance of a dot, presented at perifoveal locations (3°; see also Section 22.2.4 for a full description of the design of this study). The dot appeared with equal probability to the right or to the left of fixation and was preceded by a valid or invalid exogenous cues. As in the study of Colmenero et al. (2004), the SOA between the lateralized cue and the target was in the typical range for IOR (i.e., 900 ms). Although IOR effects were again observed, these did not differ between the two groups. However, the results revealed that detection of perifoveal targets was systematically faster in deaf than in hearing participants (59 ms on average) regardless of the attention condition (i.e., valid or invalid; Chen et al. 2006, Experiment 1).

In sum, two relevant aspects emerge from the studies that adopted an operational definition of better visual performance in deaf individuals in terms of enhanced reactivity to the stimulus. First, all reports (with the sole exception of the speeded lateralization study by Parasnis and Samar 1985) documented a response speed advantage in deaf than hearing individuals. Figure 22.1 summarizes this result graphically, by plotting the percentage difference in RTs between hearing and deaf participants with respect to the mean RT of the hearing group, in the different studies and as a function of stimulus eccentricity. With the sole exception of point [3] corresponding to the study by Parasnis and Samar (1985), all data points are above zero, indicating that deaf participants were faster than the hearing controls (on average, 13% faster with respect to the hearing group; see legend to Figure 22.1 for exact RT differences in milliseconds). Importantly, this response advantage in deaf participants emerged regardless of whether the target appeared directly at fixation or at locations further toward the periphery. This supranormal performance of deaf individuals in terms of response speed was also uninfluenced by the preceding attention cueing condition (e.g., Colmenero et al. 2004; Chen et al. 2006).

The second relevant aspect concerns the effect of attentional instructions on the performance of deaf people. Deaf participants can benefit from *valid* cueing of spatial selective attention (Parasnis and Samar 1985), but at the same time there is evidence that their performance may be less susceptible to *invalid* attention orienting (e.g., Parasnis and Samar 1985; Colmenero et al. 2004) or IOR (Colmenero et al. 2004; but see Chen et al. 2006) than hearing controls.

22.2.3 VISUAL SEARCH TASKS

One further operational definition of better visual ability in deaf individuals has been in the terms of faster search times when a prespecified target has to be found among distractors. In the visual

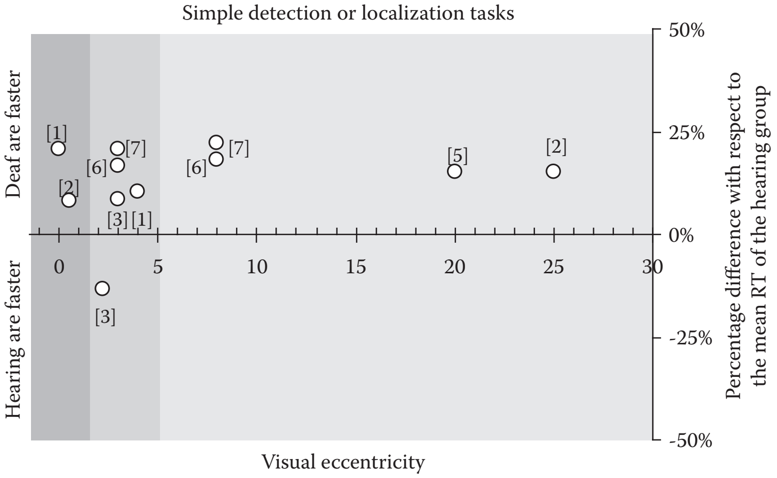

FIGURE 22.1 Difference in RT between hearing and deaf individuals (expressed as a percentage of mean RT of hearing group) across different studies, as a function of target eccentricity (in degrees). Multiple data points from the same study (e.g., see point [2]) refer to targets at different eccentricities. Positive values on *Y*-axis indicate faster response time in deaf than in hearing controls. Foveal (up to 1.5°), perifoveal (from 1.5° to 5°), and peripheral eccentricities (beyond 5°) are indicated in plot by shadings of different hues of gray. However, note that only boundaries of foveal visual field are clearly specified by anatomical landmarks; thus, the distinction between perifoveal and peripheral regions is instead conventional (we adopted here the distinction proposed by Reynolds 1993; see Section 22.1.2). Actual RT difference are as follows: [1] Reynolds (1993): 70 ms at 0°, 56 ms at 4°; [2] Loke and Song (1991): 38 ms at 0.5°, 85 ms at 25°; [3] Parasnis and Samar (1985): −58 ms at 2.2°; [4] Chen et al. (2006): 59 ms at 3°; [5] Colmenero et al. (2004): 43 ms at 20°; [6] Bottari et al. (in preparation): 52 ms at 3°, 59 ms at 8°; [7] Bottari et al. (2010): 54 ms at 3°, 59 ms at 8°.

perception literature, visual search tasks have classically been employed to distinguish perceptual processes requiring attention from perceptual processes occurring preattentively. When response time is unaffected by the number of distractors in the array, the search is typically described as preattentive (i.e., it does not require attention shift to the target in order to produce the response). By contrast, when response time increases as a function of the number of distractors in the array, the search is assumed to require serial attention shifts to the various items (Treisman 1982).

Henderson and Henderson (1973) were the first to compare the abilities of deaf and hearing children (12.5 to 16.5 years old) in a visual search task that required searching for a target letter in a letter array containing capital and lowercase letters. Although they found that the two groups did not differ in the visual search task, it should be noted that the high similarity between the target and the distractors inevitably determined a serial search in both groups. Several years later, Stivalet and colleagues (1998) also adopted a visual search task to examine visual processing in congenitally deaf and hearing adults. Unlike Henderson and Henderson (1973), they manipulated the complexity of the search by asking participants to detect the presence or absence of a Q among O's (easier search, because the target contains a single identifying feature) or of an O among Q's (harder search, because the target is lacking a feature with respect to the distractors). Moreover, to obtain a measure of visual processing time, which could be separate from the time required for motor program retrieval and response initiation/execution, all stimuli were masked after a variable interval and the dependent variable was the duration of the interval between stimuli and mask sufficient to reach 90% correct. Notably, all stimuli were presented within the perifoveal region, at an eccentricity ranging between 4.1° and 4.9°. When searching for Q among Os (easier search), both groups performed a parallel search that was unaffected by the number of distractors (4, 10, or 16). By contrast, when searching for an O among Qs (harder search), deaf adults proved substantially more efficient than hearing controls, with their visual search time (9 ms/letter) falling within the range of parallel processing (Enns and Rensink 1991), unlike hearing participants (22 ms/letter).

Further evidence along the same direction came from a visual search study by Rettenbach and colleagues (1999). They tested eight deaf and eight hearing adults, in a series of visual search task of different complexity. Unlike the study by Stivalet and colleagues (1998), the stimuli covered a wide visual angle, both vertically (20°) and horizontally (26°), thus spanning from central to peripheral locations. The results revealed more efficient visual search in deaf than hearing adults. Interestingly, when the same study was repeated in children and adolescents, deaf participants systematically underperformed with respect to the age-matched hearing controls (see also Marendaz et al. 1997), suggesting a potential developmental trajectory in the development of different visual search abilities in deaf individuals.

In sum, the studies that evaluated visual search abilities in deaf and hearing controls indicate that the range for parallel processing is ampler in deaf than hearing controls (Stivalet et al. 1998; Rettenbach et al. 1999). Furthermore, this enhanced visual ability appears to be independent of the spatial location of the stimuli, as it emerged for perifoveal (Stivalet et al. 1998) as well as peripheral stimuli (Rettenbach et al. 1999). However, the reconciliation of visual search findings with the observation of less susceptibility of deaf participants to invalid cueing or IOR (e.g., Parasnis and Samar 1985; Colmenero et al. 2004) is not straightforward. As we shall discuss later (see Section 22.3.3), assuming that both visual search and cueing effects can be accounted for by faster reorienting of attention implies a description of better visual search in deaf individuals in terms of faster and more efficient movement of the attention spotlight in space. This interpretation, however, is at odds with the description of better search as being the result of preattentive processing.

22.2.4 Visual Discrimination and Identification Tasks

One common aspect between the simple detection tasks described in Section 22.2.2 and the easy visual search tasks described in Section 22.2.3 (e.g., easy search of a Q among O's), is that both these tasks can in principle be performed without attention shifts (i.e., under distributed attention; e.g., see Bravo and Nakayama 1992; Sagi and Julesz 1984). Instead, shifts of spatial attention are certainly required to perform complex visual search tasks or to perform visual discrimination tasks. Discrimination or identification of a visual target requires binding of the multiple target features, and therefore inevitably rely on selective attention processing (e.g., Turatto et al. 2007). Furthermore, discriminating one stimulus from another implies some sort of perceptual matching with a template held in working memory. In this respect, adopting discrimination and identification task for the study of visual abilities in deaf individuals clearly implies taking a step forward in the examination of visual cognition in this auditory deprived population.

Early studies on visual discrimination in deaf individuals assessed the ability of this population in discriminating colors or complex shapes. For instance, Heider and Heider (1940) tested prelingually deaf and hearing children in a color sorting task, in which participants had to select a range of hues that could match a given standard color. Performance in the two groups was comparable, and in fact deaf children selected a wider range of hues compared to hearing children. Similarly, Suchman (1966) compared the ability of deaf and hearing individuals in an oddity discrimination task, which required the identification of an odd stimulus among other items. When the odd stimulus differed in color (5% white increase or decrease in hues), deaf participants had higher accuracy scores than hearing controls. By contrast, when the odd stimulus differed in shape (4° of internal angle with respect to the other simple shapes) hearing controls discriminated better than deaf participants. Hartung (1970) used tachistoscopic presentation to show prelingually deaf and hearing children a series of English or Greek trigrams. The task was to determine if a particular letter appeared in each trigram and to reproduce the English trigram. Although deaf performed worse than hearing children with the English trigrams, no discrimination difference emerged with the unfamiliar Greek trigrams, suggesting that any discrimination difference between groups reflected linguistic rather than perceptual difficulties.

A seminal works that adopted a visual discrimination task was conducted by Neville and Lawson in 1987. In that study, behavioral and ERP responses were recorded while 12 congenitally deaf adults (all signers, with at least one deaf parent) and 12 aged-match hearing controls performed a discrimination of direction of motion for suprathreshold visual stimuli. Visual stimuli were white squares presented at central (just above fixation) or peripheral locations (18° to the right or to the left of central fixation), with an ISI from trial onset ranging randomly between 280 and 480 ms. On 80% of the trials (termed "standards"), a single square appeared at one of these predetermined locations for 33 ms. On the remaining 20% of the trials (termed "deviants"), the square jumped slightly to one of eight possible immediately adjacent locations after the first 33 ms. The participant's task consisted in discriminating the direction of this moving square in deviant trials. Importantly, although participants fixated centrally throughout the experimental session, they were also requested to orient their attention to one of the three possible target locations (center, left, or right) across blocks. In terms of behavioral performance, deaf were faster than hearing controls (on average 70 ms) at discriminating moving targets at the peripheral locations; by contrast, no between-group difference in RT emerged for targets occurring at central locations. Instead, the two groups performed comparably in terms of sensitivity (d'): although hearing individuals showed better discrimination ability in RVF than LVF, deaf participants showed the opposite pattern. In terms of EEG response, three main findings were reported. First, the visual evoked component, termed P1 (i.e., positivity peaking at about 100 ms after the stimulus presentation), was comparable between groups regardless of whether the stimulus was standard or deviant, and regardless of stimulus location and attention condition. Second, a larger amplitude in the N1 component emerged in deaf than in hearing controls, when standard or deviant targets appeared at attended *peripheral* locations. These greater increases in cortical response due to attentional engagement in deaf than hearing controls were recorded over the occipital electrodes and in the left parietal and temporal regions. Third, the overall amplitude of N1 was larger over the right than left hemisphere in hearing controls, but larger over the left than right hemisphere in deaf individuals. VEPs in response to *central* standards and targets were instead comparable between groups. In summary, the result of the study by Neville and Lawson (1987) suggested that deaf can outperform hearing individuals in terms of reactivity (but not sensitivity) when discriminating the direction of motion for targets presented at peripheral locations. In addition, because VEP differences emerged in response to both static and moving stimuli (i.e., standard and targets, respectively) specifically in the condition of attentional engagement to peripheral locations, Neville and Lawson (1987) concluded that deafness modulates the neural system that mediates spatial attention. However, later empirical evidence has shown that a similar N1 modulation can be also documented for target monitored in distributed attention (Armstrong et al. 2002), thus challenging the conclusion that differences between deaf and hearing controls emerge selectively under conditions of focused attention.

Another study that evaluated discrimination performance in deaf and hearing participants adopting moving stimuli was conducted by Bosworth and Dobkins (2002). These authors evaluated 16 profoundly deaf signers (12 congenital), 10 hearing signers, and 15 hearing nonsigners in a direction-of-motion discrimination task. Participants were required to discriminate the direction of motion of coherent moving dots presented among random moving dots, within a single or multiple displays appearing in one or all the quadrants of the monitor. The coherent motion threshold for each participant was the number of coherently moving dots that yielded 75% correct discriminations. In addition to the number of presented displays, two other conditions were manipulated: the presence or absence of endogenous cueing (a 100% predictive spatial cue, delivered before display presentation) and stimulus duration (200 or 600 ms). Results showed no overall better performance in deaf than hearing participants when discriminating direction of motion. Intriguingly, deaf individuals tended to be faster yet less accurate than the other groups, suggesting a possible speed–accuracy trade-off in deaf but not hearing participants. The analyses also revealed that direction-of-motion thresholds

Do you mean Bosworth and Dobkins (2002a) or Bosworth and Dobkins (2002b) or both?

were less affected by cueing of attention in deaf individuals than in hearing controls (regardless of signing abilities). Furthermore, when the stimuli lasted for 600 ms, performance for the deaf group paradoxically improved with multiple rather than single displays, unlike hearing participants. Both these findings may indicate better capture of attention by a discontinuity in a complex visual scene in deaf than hearing participants, given enough time for the perceptual analysis.

Finally, in a recent study conducted in our laboratory (Bottari et al. 2010), we asked 11 congenital or early deaf and 11 hearing controls to perform a speeded shape discrimination for visual targets presented at one of eight possible locations (at 3° or 8° from central fixation). Targets were open circles lasting for 48 ms and participants were required to discriminate whether the circle was open on the left or on the right side. The result of this study showed comparable performance between deaf and hearing individuals in terms of the RT measure, even if deaf participants showed numerically faster RTs. Interestingly, deaf individuals performed worse than hearing controls in terms of accuracy, suggesting different speed–accuracy trade-off in the deaf group (see also Bosworth and Dobkins 2002).

Do you mean Bosworth and Dobkins (2002a) or Bosworth and Dobkins (2002b) or both?

In sum, the tasks requiring perceptual discrimination for suprathreshold stimuli did not provide consistent evidence in support of the notion of enhanced abilities in deaf than in hearing controls. When adopting static stimuli, better accuracy in deaf individuals compared to hearing controls have been documented only for discrimination of colour changes (Suchman 1966). Instead, the studies that required shape discrimination for static visual events failed to show any enhanced abilities in deaf individuals (Hartung 1970; Bottari et al. 2010). When adopting moving stimuli, faster RTs in deaf subjects than in hearing participants have been documented only by Neville and Lawson (1987), selectively for events at peripheral locations. Instead, Bosworth and Dobkins (2002) showed an overall comparable performance between deaf and hearing controls when discriminating coherence of motion.

Do you mean Bosworth and Dobkins (2002a) or Bosworth and Dobkins (2002b) or both?

22.2.4.1 Visual Discrimination with Flanker Interference

A series of experiments adopting discrimination or identification tasks also evaluated the effect of entirely task-irrelevant competing stimuli on discrimination performance. The main rationale underlying this manipulation is that any bias for processing peripheral events more than central ones in the deaf population should emerge as larger interference effects of peripheral distracting information on central targets (or, conversely, as smaller interference effects of central distractors on peripheral targets).

One of the first examples of this experimental paradigm is the study by Reynolds (1993). In addition to the speeded lateralization task already described in Section 22.2.2, deaf and hearing participants were required to identify the figures that appeared 4° to the left or right of central fixation. Target figures were presented alone or together with concurrent stimuli delivered at fixation (simple shapes, outline drawings of familiar objects or letters). Overall, no recognition accuracy advantage emerged in deaf than in hearing participants (62% vs. 58% correct). The only difference between deaf and hearing controls emerged with respect to hemifield of stimulus presentation. Deaf participants showed an LVF advantage in identification accuracy when concurrent stimuli at fixation were absent or were simple shapes, and an RVF advantage when concurrent stimuli at fixation consisted of drawings or letter stimuli. The reversed pattern of results emerged in hearing controls.

One influential study that also examined identification with concurrent distractors at central and peripheral locations has been conducted several years later by Proksch and Bavelier (2002). In three experiments, they tested deaf students (all congenital and signers) and hearing controls (including a group of participants born from deaf parents, who learned sign language in infancy) in a speeded shape identification task. The target shape (square or diamond) was presented inside one of six circular frames, arranged around fixation in a ring of 2.1° of radius. In each trial, a distracting shape was presented concurrently with the target, either in the center of the screen (0.5° to the left or right of fixation) or outside the target ring (4.2° to the left or right of fixation). The distractor was an item from the target set, either compatible (e.g., target: diamond; distractor: diamond) or incompatible (e.g., target: diamond; distractor: square), or else a neutral shape. Finally, a variable number (0, 1, 3, or 5) of filler shapes was introduced in the empty circular frames of the target ring to manipulate perceptual load across trials. Participants were instructed to identify the target as quickly as possible, while ignoring all other distracting shapes. Overall, target identification proved longer for deaf than hearing participants (Experiment 1: 765 vs. 824 ms, respectively; Experiment 3: 703 vs. 814 ms). All experiments consistently revealed the interfering effect of perceptual load and lateralized distractors on RT performance. Critically, however, peripheral distractors proved more distracting for deaf individuals, whereas central ones were more distracting for hearing controls (regardless of whether they were signers). This led Proksch and Bavelier (2002) to conclude that "the spatial distribution of visual attention is biased toward the peripheral field after early auditory deprivation" (p. 699).

A related study was conducted by Sladen and colleagues (2005), using the classic flanker interference task developed by Eriksen and Eriksen (1974). Ten early deaf (onset before 2 years of age, all signers) and 10 hearing adults were asked a speeded identification of a letter (H or N) presented either in isolation (baseline) or surrounded by four response-compatible letters (two on either side; e.g., HHHHH) or response-incompatible letters (e.g., NNHNN). Letters were presented 0.05°, 1°, or 3° apart from each other. The results showed that letter discrimination was faster in hearing than in deaf participants in each of the experimental conditions including the baseline (e.g., between 50 and 81 ms difference, for incompatible stimuli), but this was accompanied by more errors in the hearing group during incompatible trials. Interestingly, the two groups also differed in their performance with the 1° spacing between target and flankers: the incongruent flanker cost emerged for both groups, but was larger in deaf than in hearing participants. Again, this finding is compatible with the notion that deaf individuals may have learned to "focus their visual attention in front of them in addition to keeping visual resources allocated further out in the periphery" (Sladen et al. 2005, p. 1536).

The study by Chen et al. (2006), described in Section 22.2.2, also adopted a flanker interference paradigm. On each trial, participants were presented with a raw of three horizontally aligned boxes, of which the central one contained the target and the side ones (arranged 3° on either side) contained the distractors. The task required a speeded discrimination among four different colors. Two colors were mapped onto the same response button, whereas the other two colors were mapped onto a different response button. Simultaneous to target presentation, a flanker appeared in one of the lateral boxes. The flanker was either identical to the target (thus leading to no perceptual conflict and no motor response conflict), or different in color with respect to the target but mapped onto the same motor response (thus leading only to a perceptual conflict) or different in color with respect to the target and mapped onto a different response than the target (thus leading to perceptual and motor conflict). Finally, spatial attention to the flanker was modulated exogenously by changing the thickness and brightness of one of the lateral boxes at the beginning of each trial. Because the time interval between this lateralized cue and the target was 900 ms, this attentional manipulation created an IOR effect (see also Colmenero et al. 2004). Overall, color discrimination was comparable between groups in terms of reaction times (see also Heider and Heider 1940). However, the interference determined by the flankers emerged at different levels (perceptual vs. motor response) in deaf and hearing participants, regardless of the cueing condition. Hearing participants displayed a flanker interference effect both for flankers interacting at the perceptual and response levels. In contrast, deaf participants showed flanker interference effects at the response level, but not at the perceptual level.

Finally, Dye et al. (2007) asked 17 congenitally deaf and 16 hearing adults to perform a speeded discrimination about the direction of a central arrow (pointing left or right) presented 1.5° above or below central fixation and flanked by peripheral distractors (other arrows with congruent or incongruent pointing directions, or neutral lines without arrowheads). A cue consisting of one or two asterisks presented 400 ms before the onset of the arrows oriented attention to central fixation, to the exact upcoming arrow location, or to both potential arrow locations (thus alerting for stimulus appearance without indicating the exact target location). The findings showed comparable effects of orienting spatial cues in hearing and deaf individuals, as well as comparable alerting benefits. Interestingly, when the number of flanker arrows was reduced to 2 and their relative distance from the central arrow was increased to 1°, 2°, or 3° of visual angle, deaf participants displayed stronger flanker interference effects in RTs compared to hearing controls.

In sum, the studies that measured allocation of attentional resources in the visual scene using flanker interference tasks showed larger interference from distractors in deaf than in hearing participants (Proksch and Bavelier 2002; Sladen et al. 2005; Chen et al. 2006; Dye et al. 2007). However, although Proksch and Bavelier (2002) showed enhanced distractor processing in deaf than in hearing adults at 4.2° from central fixation, Sladen et al. (2005) showed enhanced distractor processing at 1° from central fixation, but comparable distractor processing at 3°. Finally, Dye et al. (2007) showed increased flanker interference in deaf than in hearing controls regardless of whether the two distracting items were located at 1°, 2°, or 3° from fixation. These mixed results suggest that some characteristics of the visual scene and task, other than just the peripheral location of the distractors, could play a role. These additional characteristics might include the degree of perceptual load, the amount of crowding, or the relative magnification of the stimuli.

22.2.5 VISUAL TASKS OF HIGHER COMPLEXITY

Beyond visual discrimination or identification tasks, our attempt to relate single experimental paradigms with single operational definitions of better visual abilities in deaf individuals becomes inevitably more complex. For instance, the visual enumeration test and the Multiple Object Tracking test recently adopted by Hauser and colleagues (2007), the change detection task adopted by our group (Bottari et al. 2008, in preparation), or the studies on speech-reading ability of deaf individuals (e.g., Bernstein et al. 2000; Mohammed et al. 2005) can hardly be reduced to single aspects of visual processing. Nonetheless, we report these studies in detail because they are informative about the selectivity of the performance enhancements observed in the deaf population.

Not found in the Reference list; please provide the details for this citation.

Hauser and colleagues (2007) evaluated 11 congenital deaf and 11 hearing controls in an enumeration task, asking participants to report on a keyboard the number of briefly flashed static targets in a display, as quickly and accurately as possible. The task was either conducted with a field of view restricted to 5° around fixation or with a wider field of view of 20° around fixation. In such enumeration tasks, participants typically display a bilinear performance function, with fast and accurate performance with few items (subitizing range), and a substantially greater cost in terms of reaction times and accuracy as the number of items increase. The results of Hauser et al. (2007) showed comparable subitizing performance in deaf and hearing individuals, regardless of which portion of visual field was evaluated. A second experiment conducted on 14 congenital deaf and 12 hearing control, adapted the Multiple Object Tracking test (Pylyshyn 1989). In this task, participants are presented with a number of moving dots of which a subset is initially cued. When the cues disappear, participants are required to keep track of the dots that were initially cued until one of the dots in the set is highlighted. Participants have to indicate whether such dot was also cued at the beginning of the trial. Despite that this task was performed on a wide field of view, to maximize the possibility any difference between deaf and hearing participants, no sensitivity difference emerged. The authors concluded that "early deafness does not enhance the ability to deploy visual attention to several different objects at once, to dynamically update information in memory as these objects move through space, and to ignore irrelevant distractors during such tracking" (Hauser et al. 2007, p.183).

Not found in the Reference list; please provide the details for this citation.

Two studies from our group evaluated the ability of deaf and hearing individuals to discriminate between the presence or absence of a change in a visual scene (Bottari et al. 2008, in preparation). In these studies, two visual scenes were presented one after the other in each experimental trial, separated by an entirely blank display. Each visual scene comprised four or eight line-drawing images, half of which were arranged at 3° from central fixation and the other half were arranged at 8°. On

50% of the trials, the second scene was entirely identical to the first (i.e., no change occurred), whereas on the other 50% of the trials one drawing in the first scene changed into a different one in the second scene. The participant's task was to detect whether the change was present or absent. When comparing two alternating visual scenes, any change is typically detected without effort because it constitutes a *local* transient that readily attracts exogenous attention to the location where the change has occurred (O'Regan et al. 2000). However, if a blank image is interposed between the two alternating scenes (as in the adopted paradigm), any single part of the new scene changes with respect to the previous blank image, resulting in a *global* rather than local transient. The consequence of this manipulation is that attention is no longer exogenously captured to the location of change, and the change is noticed only through a strategic (endogenous) scan of the visual scene (the so-called "change blindness" effect; Rensink 2001). Thus, the peculiarity of this design was the fact that all local transients related to target change or target onset were entirely removed. This produced an entirely endogenous experimental setting, which had never been adopted in previous visual tasks with deaf people (see Bottari et al. 2008 for further discussion of this point). The result of two studies (Bottari et al. 2008, in preparation) revealed that sensitivity to the change in deaf and hearing adults was comparable, regardless of change in location (center or periphery), suggesting that the sensitivity to changes in an entirely transient-free context is not modulated by deafness. Furthermore, this conclusion was confirmed also when the direction of endogenous attention was systematically manipulated between blocks by asking participants to either focus attention to specific regions of the visual field (at 3° or 8°) or to distribute spatial attention across to the whole visual scene (Bottari et al. 2008). In sum, even visual tasks tapping on multiple stages of nonlinguistic visual processing (and particularly visual working memory) do not reveal enhanced processing in deaf than in hearing controls. Once again, the absence of supranormal performance was documented regardless of the eccentricity of the visual stimulation. Furthermore, the results of Bottari et al. (2008) indicate that focusing endogenous attention is not sufficient to determine a between-group difference. It remains to be ascertained whether the latter results (which is at odds with the behavioral observation of Neville and Lawson 1987 and with the neural observation of Bavelier et al. 2000) might be the consequence of having removed from the scene all target-related transients that could exogenously capture the participant's attention.

A different class of complex visual tasks in which deaf individuals were compared to hearing controls evaluated speech-reading abilities (also termed lip-reading). Initial studies on speech-reading suggested that this ability was considerably limited in hearing controls (30% words or fewer correct in sentences according to Rönnberg 1995) and that "the best totally deaf and hearing-impaired subject often perform only as well as the best subjects with normal hearing" (Summerfield 1991, p. 123; see also Rönnberg 1995). However, two later contributions challenged this view and clearly showed that deaf individuals can outperform hearing controls in speech-reading tasks. Bernstein et al. (2001) asked 72 deaf individuals and 96 hearing controls to identify consonant–vowel nonsense syllables, isolated monosyllabic words and sentences presented through silent video recordings of a speaker. The results showed that deaf individuals were more accurate than hearing controls, regardless of the type of the verbal material. In agreement with this conclusion, Auer and Bernstein (2007) showed a similar pattern of results in a study that evaluated identification of visually presented sentences in an even larger samples of deaf individuals and hearing controls (112 and 220, respectively). It is important to note that both studies did not include deaf individuals who used sign language as preferential communication mode, thus relating these enhanced lip-reading skills to the extensive training that deaf individuals had throughout their lives.

For the purpose of the present review, it is important to note that speechreading is a competence that links linguistic and nonlinguistic abilities. Mohammed and colleagues (2005) replicated the observation that deaf individuals outperform hearing controls in lip-reading skills. Furthermore, they showed that the lip-reading performance of deaf individual (but not hearing controls) correlated with the performance obtained in a classical coherence motion test (see also Bosworth and Dobkins 1999; Finney and Dobkins 2001), despite that the overall visual motion thresholds were entirely comparable between the two groups (in agreement with what we reported in Section 22.2.1). In sum, lip-reading is a visual skill that systematically resulted enhanced in deaf individuals compared to hearing controls. Intriguingly, in deaf individuals this skill appears to be strongly interconnected with the ability of perceiving motion in general, supporting the notion that visual motion perception has a special role in this sensory-deprived population.

22.3 A TRANSVERSAL VIEW ON LITERATURE

The first aim of the present review was to provide a detailed report on the empirical evidence about visual abilities in profound deafness, organized as a function of task. This served the purpose of highlighting the different operational definitions of "better visual ability" adopted in the literature and examined the consistency of the findings across tasks. The second aim was to evaluate to what extent four distinct aspects, which are transversal to the different behavioral tasks, can contribute to the understanding of the heterogeneity of the empirical findings. In particular, the aspects considered were: (1) diversity in deaf individuals sample characteristics; (2) visual characteristics of the target stimulus; (3) target eccentricity; and (4) the role of selective spatial attention.

22.3.1 Enhanced Reactivity Rather than Enhanced Perceptual Processing

One aspect that clearly emerges from our task-based review of the literature is that the operational definitions of better visual abilities in deaf individuals in terms of *enhanced perceptual processing* of the visual stimulus do not reveal systematic differences between deaf and hearing controls. This conclusion is particularly clear in all those studies that examined perceptual processing for stimuli at or near threshold (see Section 22.2.1), but it is also confirmed by studies that required discrimination or identification for stimuli above thresholds (see Section 22.2.4) and by studies that also took the role of visual working memory into account (see Section 22.2.5). In the case of discrimination and identification tasks, only one report has shown a behavioral discrimination advantage for deaf than hearing controls (e.g., see the RT difference for stimuli at peripheral locations in the work of Neville and Lawson 1987), whereas in all the remaining studies a between-group difference emerged only in the way attention instructions or flankers impacted on the performance of deaf and hearing participants, but not in terms of overall processing advantage for the deaf group. In striking contrast with this pattern of results, almost all studies adopting simple detection or lateralization tasks have shown a reactivity advantage (occurring in a range between 38 and 85 ms) in deaf over hearing participants. Furthermore, when these studies are considered, collectively enhanced reactivity in deaf participants do not appear to be modulated by stimulus eccentricity in any obvious way (see Figure 22.1). Finally, although attentional manipulations did impact on simple detection performance (e.g., Colmenero et al. 2004; Chen et al. 2006), the between-group difference did not emerge selectively as a function of the attentional condition.

The observation that better visual abilities in deaf individuals emerge mainly for tasks designed around speeded simple detection of the stimulus, rather than tasks designed around discrimination performance, suggests that profound deafness might *not* result in enhanced perceptual representation of visual events. Instead, any modification of visual processing in deaf individuals may occur at the level of visual processing speed, or at the level response selection/generation or at both these stages (for further discussion of this point, see Bottari et al. 2010). Prinzmetal and colleagues (2005, 2009) recently proposed that performance enhancement could either reflect perceptual channel *enhancement* or perceptual channel *selection*. Although channel enhancement would result in better sensory representation of the perceptual events, channel selection would only result in faster processing. We suggest that enhanced visual abilities in deaf individuals may reflect channel selection more than channel enhancement, and that enhanced reactivity may be the core aspect of the compensatory cross-modal plasticity occurring in this sensory-deprived population. In the context of the present review, it is also interesting to note that Prinzmetal and colleagues (2005, 2009) have associated channel enhancements with endogenous attention selection, but channel selection with exogenous attention capture (see also Section 22.3.3).

22.3.2 Role of Deaf Sample Characteristics and Visual Stimulus Characteristics are Relevant but Not Critical

Several investigators have suggested that the heterogeneity of the results observed in the literature on visual abilities in deaf individuals might reflect the diversities in the characteristics of deaf participants recruited across the different studies (e.g., Bavelier et al. 2006; Hoemann 1978). Although this perspective appears very likely, to the best of our knowledge systematic studies on the impact of critical variables, such as deafness onset (early or late) or preferred communication mode, on the deaf visual skill have not been conducted. Similarly, the exact role of amount of hearing loss and etiology of deafness remains to be ascertained. Our review indicates that the vast majority of investigations have tested congenital or early deaf participants, using primarily sign language. However, our review also challenges the idea that sample characteristics alone can account for the variability in the results. Even those studies that restricted the population to "deaf native signers" (Bavelier et al. 2006) did not find systematically better abilities in deaf than in hearing controls. For instance, Hauser and colleagues (2007) pointed out that the comparable performance between deaf and hearing controls in their visual enumeration and visual working memory tasks emerged despite the fact that the population of deaf native signers tested in the study was identical to that recruited in previous studies from the same research group that instead documented enhanced performance with respect to hearing controls (Hauser et al. 2007, p. 184).

Specificity of the target stimulus characteristics is also unlikely to explain the heterogeneity of the findings. The hypothesis that motion stimuli are more effective than the static one in determining enhanced visual abilities in deaf individuals is, at the very least, controversial in light of the current review of the literature. Studies adopting perceptual threshold tasks consistently documented comparable performance between deaf and hearing participants regardless of whether the stimuli were static (as in Bross 1979a, 1979b) or moving (e.g., Bosworth and Dobkins 1999; Brozinsky and Bavelier 2004; but see Stevens and Neville 2006). Instead, in simple detection tasks, enhanced reactivity in deaf than in hearing participants have been documented primarily with static stimuli. Finally, using complex visual tasks tapping on working memory capacities, Hauser and colleagues (2007) showed comparable performance between deaf and hearing individuals regardless of whether stimuli were stationary (enumeration task) or moving (Multiple Object Tracking task). One piece of evidence that could support the notion that motion stimuli are more effective than static ones in eliciting differences between the two groups is the observation that discrimination for moving stimuli at the visual periphery (18°) is better for deaf than hearing participants (Neville and Lawson 1987), whereas discrimination for static stimuli also appearing toward the periphery (8°) is not (Bottari et al. 2010). However, the evident discrepancy in stimulus location between the two studies prevents any definite conclusion, which could only be obtained by running a direct comparison of deaf and hearing performance using stimuli differing in the motion/static dimension, while other variables are held fixed.

22.3.3 Role of Target Eccentricity and Selective Visual Attention is Critical but Underspecified

The present review supports the notion that representation of the visual periphery in the profoundly deaf might indeed be special. It is clearly more often the case that differences between the two groups emerged for stimuli delivered at peripheral than central locations (e.g., Loke and Song 1991; Bottari et al. 2010, in preparation; Neville and Lawson 1987). However, it is also clear that the central or peripheral location of the stimulus is *not* a definite predictor of whether deaf and hearing participants will differ in their performance. Better performance in deaf than in hearing participants has been documented with both central and peripheral stimuli (e.g., see Section 22.2.2). Conversely, threshold tasks proved ineffective in showing between-group differences, regardless of whether stimuli were delivered centrally or peripherally. Thus, the question of what exactly is special in the representation of peripheral stimuli in deaf individuals has not yet been resolved.

One observation relevant to this problem may be the recent finding from our group that the differential processing for central and peripheral locations in deaf and hearing people emerge independently from orienting of attention. Bottari et al. (2010) showed no RT cost when processing peripheral than central items in deaf participants, unlike hearing controls. Importantly, this occurred in a task (simple detection) that requires no selective allocation of attentional resources (Bravo and Nakayama 1992). This implies a functional enhancement for peripheral portions of the visual field that cannot be reduced to the differential allocation of attentional resources alone (see also Stevens and Neville 2006 for related evidence). Because the cost for peripheral than central processing in hearing controls is classically attributed to the amount of visual neurons devoted to the analysis of central than peripheral portion of the visual field (e.g., Marzi and Di Stefano 1981; Chelazzi et al. 1988), it can be hypothesized that profound deafness can modify the relative proportion of neurons devoted to peripheral processing or their baseline activity. Note that assuming a different neural representation of the peripheral field also has implication for studies that examined the effects of peripheral flankers on central targets (e.g., Proksch and Bavelier 2002; Sladen et al. 2005), that is, it suggests that the larger interference from peripheral flankers in deaf individuals could at least partially result from enhanced sensory processing of these stimuli, rather than attentional bias to the periphery (similar to what would be obtained in hearing controls by simply changing the size or the saliency of the peripheral flanker).

The final important aspect to consider is the role of selective attention in enhanced visual abilities of deaf individuals. Our review of the literature concurs with the general hypothesis that deafness somehow modulates selective visual attention (e.g., Parasnis 1983; Neville and Lawson 1987; Bavelier et al. 2006; Mitchell and Maslin 2007). However, it also indicates that any further development of this theoretical assumption requires a better definition of which aspects of selective attention are changed in this context of cross-modal plasticity. To date, even the basic distinction between exogenous and endogenous processes have largely been neglected. If this minimal distinction is applied, it appears that endogenous orienting alone does not necessarily lead to better behavioral performance in deaf than in hearing controls. This is, first of all, illustrated by the fact that endogenous cueing of spatial attention (e.g., using a central arrow, as Parasnis and Samar 1985 have done) can produce similar validity effects in deaf and hearing individuals. Furthermore, a recent study by Bottari et al. (2008), which examined endogenous orienting of attention in the absence of the exogenous captures induced by target onset, revealed no difference whatsoever between deaf and hearing participants, regardless of whether attention was focused to the center, focused to the periphery, or distributed across the entire visual scene. By contrast, several lines of evidence suggest that the exogenous component of selective attention may be more prominent in deaf than in hearing people. First, studies that have adapted the cue–target paradigm have shown more efficient detection in deaf than in hearing adults, when the target occurs in a location of the visual field that have been made unattended (i.e., invalid; see Parasnis and Samar 1985; Colmenero et al. 2004, Experiment 1; Bosworth and Dobkins 2002). Second, paradigms that adopted an SOA between cue and target that can lead to IOR also revealed that deaf participants are less susceptible to this attention manipulation and respond more efficiently to targets appearing at the supposed inhibited location with respect to controls (e.g., Colmenero et al. 2004, Experiment 2). Finally, deaf participants appear to be more distracted than hearing controls by lateralized flankers that compete with a (relatively) more central target (Dye et al. 2008; Proksch and Bavelier 2002; Sladen et al. 2005), as if the flanker onset in the periphery of the visual field can capture exogenous attention more easily.

Do you mean Bosworth and Dobkins (2002a) or Bosworth and Dobkins (2002b) or both?

In the literature on visual attention in deaf individuals, the latter three findings have been interpreted within the spotlight metaphor for selective attention (Posner 1980), assuming faster shifts of visual attention (i.e., faster reorienting) in deaf than in hearing participants. However, this is not the only way in which attention can be conceptualized. A well-known alternative to the spotlight metaphor of attention is the so-called gradient metaphor (Downing and Pinker 1985), which assumes a peak of processing resources at the location selected (as a result of bottom-up or top-down signals) as well as a gradual decrease of processing resources as the distance from the selected location increases. Within this alternative perspective, the different performance in deaf participants during the attention tasks (i.e., enhanced response to targets at the invalid locations, or more interference from lateralized flankers) could reflect a less steep gradient of processing resources in the profoundly deaf. Although it is premature to conclude in favor of one or the other metaphor of selective attention, we believe it is important to consider the implications of assuming one instead of the other. For instance, the gradient metaphor could provide a more neurally plausible model of selective attention. If one assumes that reciprocal patterns of facilitation and inhibition in the visual cortex can lead to the emergence of a saliency map that can contribute to the early filtering of bottom-up inputs (e.g., Li 2002), the different distribution of exogenous selective attention in deaf individuals could represent a modulation occurring at the level of this early saliency map. Furthermore, assuming a gradient hypothesis may perhaps better reconcile the results obtained in the studies that adopted the cue–target and flanker paradigms in deaf individuals, with the results showing more efficient visual search pattern in this population. Within the gradient perspective, better visual search for simple features or faster detection of targets at invalidly cued locations could both relate to more resources for preattentive detection of discontinuities in deaf individuals.

22.4 CONCLUSIONS AND FUTURE DIRECTIONS

When taken collectively, the past 30 years of research on visual cognition in deaf individuals may, at first sight, appear heterogeneous. However, our systematic attempt to distinguish between the different operational definitions of “better visual abilities” in deaf individuals proved useful in revealing at least some of the existing regularities in this literature and specify under which context the compensatory hypothesis is consistently supported.

First, the remarkable convergence of findings in the studies that adopted simple detection tasks and the mixed findings of the studies that adopted discrimination paradigms (either for near-threshold or suprathreshold stimuli), suggests that enhanced visual abilities in deaf individuals might be best conceptualized as enhanced reactivity to visual events, rather than enhanced perceptual representations. In other words, deaf individuals “do not see better,” but react faster to the stimuli in the environment. If this conclusion is true, reactivity measures may prove more informative than accuracy reports when comparing deaf and hearing controls, even when discrimination tasks are adopted. This raises the issue of which may be the neural basis for enhanced reactivity in deaf individuals and at which processing stage it may emerge (i.e., perceptual processing, response preparation/execution, or both). In addition, it raises the question of which functional role enhanced reactivity may play in real life. In this respect, the multisensory perspective that we have introduced at the beginning of this chapter may be of great use for understanding the ecological relevance of this phenomenon. If audition constitutes a fundamental guidance for reorienting our exploratory behavior and it is a dedicated system for detecting and reacting to discontinuities, one could hypothesize that faster reactivity to the visual events in deaf individuals may primarily serve the purpose of triggering orienting responses. Because all the evidence we have reviewed in this chapter originated from paradigms in which overt orienting was completely prevented, this question remains open for future research.

The second consistency that emerged from our review concerns the modulation that profound deafness determines the representation of peripheral visual space and visual attention. Although a number of evidence in the literature converges in supporting this conclusion, the challenge for future research is the better specification of the operational description of both these concepts. Without such an effort, the concepts of enhanced peripheral processing and enhanced visual attention are at risk of remaining tautological redefinitions of the empirical findings. As discussed above for the example of selective attention, even a minimal description of which aspects of selective attention may be changed by profound deafness or a basic discussion about of the theoretical assumptions underlying the notion of selective attention can already contribute to the generation of novel predictions for empirical research.

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