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Article *in* Restorative neurology and neuroscience · January 2010

DOI: 10.3233/RNN-2010-0502 · Source: PubMed

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Restorative Neurology and Neuroscience 28 (2010) 167–179
DOI 10.3233/RNN-2010-0502
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Enhanced reactivity to visual stimuli in deaf individuals

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Abstract. *Purpose*: Several studies have reported faster response time to visual stimuli in profoundly deaf individuals. This result is often linked to the processing of peripheral targets, and it is assumed to occur in relation to attention orienting. We evaluated whether enhanced reactivity to visual events in profoundly deaf individuals can be explained by faster orienting of visual attention alone.

Methods: We examined 11 deaf individuals and 11 hearing controls, in a simple detection task and in a shape discrimination task. While simple detection can be performed under distributed attention, shape discrimination requires orienting of spatial attention to the target. The same visual targets served for both tasks, presented at central or peripheral locations and corrected for cortical magnification.

Results: The simple detection task revealed faster RTs in deaf than hearing controls, regardless of target location. Moreover, while hearing controls paid a cost in responding to peripheral than central targets, deaf participants performed equally well regardless of target eccentricity. In the shape discrimination task deaf never outperformed hearing controls.

Conclusions: These findings reveal that enhanced reactivity to visual stimuli in the deaf cannot be explained only by faster orienting of visual attention and can emerge for central as well as peripheral targets. Moreover, the persisting advantage for peripheral locations in the deaf, observed here under distributed attention, suggests that this spatially-selective effect could result from reorganised sensory processing rather than different attentional gradients.

Keywords: deafness, visual attention, plasticity, multisensory

1. Introduction

The consequences of long-term auditory deprivation due to profound deafness on perception, language and cognition are a fundamental topic in crossmodal plasticity research (for recent reviews and clinical implications see Marschark and Hauser, 2008). One aspect of deaf cognition that has received considerable attention in recent years is the functional and anatomical reorganisation that occurs within the visual modality (e.g. Bavelier et al., 2006; Dye et al., 2008; Mitchell and Maslin, 2007). A key observation of this recent literature is that not all aspects of visual processing are enhanced in profound deafness, thus revealing functional dissociations that can shed light into the mechanisms of cross-modal plasticity that occur in this sensory deprived population. In the present work, we will start by briefly reviewing some of the most relevant features of visual processing in the profoundly deaf individuals, and then we will report an experimental investigation on the functional mechanisms that could subtend the enhancement of response speed observed in this population.

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1.1. Spatial selectivity of enhanced visual abilities in the deaf

An empirical observation that has been repeatedly reported concerns the spatial selectivity of enhanced visual processing in deaf individuals. Enhanced performance in this population has typically been described for visual stimuli occurring towards peripheral portions of the visual field than stimuli occurring towards the centre.[1]

Deaf individuals show faster reaction times when detecting or discriminating single peripheral visual targets (e.g., Colmenero et al., 2004; Loke and Song, 1991; Neville and Lawson, 1987; see also Bavelier et al., 2000, 2001; Bosworth and Dobkins, 2002). By contrast, reaction time differences between deaf and hearing controls do not emerge for single targets appearing at or near central fixation (Neville and Lawson, 1987; Poizner and Tallal, 1987). Similarly, when concurrent central and peripheral targets compete for attentional resources, deaf individuals preferentially orient visual attention towards peripheral than central locations (Chen et al., 2006; Proksch and Bavelier, 2002; Sladen et al., 2005).

Enhanced performance at peripheral locations is compatible with the notion that, under normal conditions, the auditory system provides important information about the events that occur outside the field of view. In the absence of audition, visual processing may be recalibrated to favour rapid detection of events outside foveal regions of the retina, in the attempt to monitor the environment through peripheral vision instead of audition (Loke and Song, 1991; Parasnis and Samar, 1985). Evidence in support of this functional account of crossmodal plasticity in deaf individuals comes from a recent study by Stevens and colleagues (2006) that revealed enlarged useful field of view at the extreme periphery, when detecting motion stimuli. In that study, deaf individuals and hearing controls were tested in a kinetic perimetry task to evaluate the extension of the visual field in which the presence of moving stimuli can be detected. Interestingly, animal studies have revealed direct connections between auditory and visual cortices for peripheral portions of the visual field (e.g., Falchier et al., 2002), thus offering a possible neural substrate for this spatially selective enhancement.

1.2. Enhanced response speed rather than sensitivity

A further general observation concerning visual processing in deaf individuals is that supra-normal abilities at the behavioural level have mainly been documented in tasks measuring speed rather sensitivity responses. Enhanced visual abilities have been reported in studies adopting speeded tasks (e.g., Chen et al., 2006; Colmenero et al., 2004; Loke and Song, 1991), with an overall response time (RT) benefit for profoundly deaf individuals of over 40 ms. By contrast, studies that examined accuracy measures for near-thresholds or above-threshold visual stimuli often failed to show enhanced abilities in deaf individuals with respect to hearing controls (e.g., Bosworth and Dobkins, 2002; Brozinsky and Bavelier, 2004; Finney and Dobkins, 2001; Nava et al., 2008; Neville and Lawson, 1987; for similar results in frequency discrimination task for vibrotactile stimuli see also Levänen and Hamdorf, 2001).

No accuracy difference between deaf individuals and hearing controls emerged for visual contrast sensitivity (Finney and Dobkins, 2001) or luminance change detection (Bavelier et al., 2000, 2001). Similarly, perceptual thresholds for motion velocity (Brozinsky and Bavelier, 2004) or motion direction changes (Bosworth and Dobkins, 2002) appeared to be comparable in the two groups. Intriguingly, the latter study on motion direction sensitivity revealed a slight speed-accuracy trade-off in the performance of the deaf individuals: their sensitivity performance was slightly worse compared to hearing controls, but their response speed was numerically faster (see Bosworth and Dobkins, 2002, p. 160). Further evidence for comparable sensitivity in deaf individuals and hearing controls, accompanied by faster RTs in the deaf participants, have also been documented by Neville and Lawson (1987) who showed that discrimination accuracy for motion direction at peripheral locations is comparable in the two groups, but deaf individuals perform significantly faster (70 ms on average). In addition, Nava and colleagues (2008) showed that deaf participants were on average 100 ms faster than hearing controls when judging the temporal order of visual stimuli under the most demanding (i.e., shortest) asynchronies, in spite of comparable temporal sensitivity.

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[1] The actual eccentricities associated with the terms ‘central’ and, particularly, ‘peripheral’ locations varied considerably across the different studies. Researchers referred to central locations both when the stimulus was presented directly at fixation (e.g., Poizner and Tallal, 1987) or peri-foveally (Neville and Lawson, 1987). Instead, peripheral locations in the visual field ranged from eccentricities of 3 degrees (Chen et al., 2006) to eccentricities of 20 degrees or more (Colmenero et al., 2004; Loke and Song, 1991; Stevens and Neville, 2006).

Finally, in a flanker interference study (Proksch and Bavelier, 2002) deaf participants showed more interference from peripheral than central distractors when compared to hearing controls, but this finding emerged only in terms of RTs and not for the accuracy measure.

The observation that better visual abilities in the deaf emerge mainly for reactivity than accuracy or sensitivity measures argues against the hypothesis that profound deafness results in enhanced perceptual representation of the visual events. By contrast, it suggests modifications of visual processing that occur either at the level of processing speed, or at the level response selection/generation or at both these stages. The latter distinction maps nicely on two types of performance enhancements recently proposed by Prinzmetal and colleagues (2005, 2008): perceptual channel enhancement vs. perceptual channel selection. While channel enhancement would result in better sensory threshold for the perceptual event (and has been associated with endogenous attention selection), channel selection would only result in faster processing of the sensory event (and has been associated with exogenous attention capture).

1.3. *Enhanced processing of visual features that activate the dorsal visual stream*

Several authors have proposed that enhanced visual abilities in deaf individuals emerge selectively for the analysis of visual features that are preferentially processed within the visual-for-action pathway, associated with the dorsal visual stream (Milner and Goodale, 1995). These visual features include moving patterns (Armstrong et al., 2002; Bavelier et al., 2000, 2001; Bosworth and Dobkins, 2002) as well as abrupt onsets in the scene (Chen et al., 2006; Colmenero et al., 2004; Loke and Song, 1991).

For instance, in two functional neuroimaging (fMRI) studies, Bavelier and colleagues (2000, 2001) have shown that cortical activation in the MT+ complex was stronger for deaf individuals than hearing controls, when attending to motion stimuli at peripheral locations. Motion stimuli were also shown to activate the right auditory cortex in the deaf participants (Fine et al., 2005; Finney et al., 2001). Finally, an event-related potential (ERP) study by Armstrong and colleagues (2002; see also Neville and Bavelier, 2002) revealed enhanced cortical responses (larger N1 components) in deaf individuals compared to hearing controls in response to task-irrelevant moving stimuli at peripheral locations, even without specific attentional instructions. Importantly, when cortical activity was compared between groups for coloured stimuli (preferentially processed by the ventral visual stream), enhanced cortical responses for deaf individuals than hearing participants no longer emerged. This specific observation led to the suggestion that crossmodal plasticity in profoundly deaf individuals could mainly involve cortical reorganisations occurring within the dorsal stream of visual processing (Armstrong et al., 2002; Bavelier et al., 2006; Neville and Bavelier, 2002).

Further evidence in support of the notion that enhanced visual abilities may depend upon aspects of visual processing that tap onto the dorsal visual stream functions also comes from one recent study of our group (Bottari et al., 2008; see also Bottari et al., under review). We used a behavioural paradigm known as the ‘flicker task’ (Phillips and Singer, 1974; Rensink, 2002), to systematically mask all transient events related to target onset that could capture the observer’s visual attention to the target. The general experimental procedure consisted of two alternating visual scenes composed of different drawings, separated by a blank display. In half of the trials, one of the drawings changed into a different one in the second scene, and participants were required to detect whether a changed had occurred or not. Critically, with such a paradigm any local transient related to the occasional change is masked by the fact that the entire visual scene is a global change with respect to the interposed blank display (a procedure known as the flicker version of the change blindness task; Rensink, 2002). Results showed that when all visual transients related to target onset were masked, no performance difference between deaf individuals and hearing controls emerged in response to the visual events (see Bottari et al., 2008). The results of this study highlights the possibility that visual compensations in deafness may be connected to the presence of task-relevant transients, a visual feature that strongly characterises responses of the dorsal visual stream.

1.4. *The role of attention orienting in enhanced visual processing of the deaf*

A final aspect that should be considered is the role of spatial selective attention in enhanced visual processing of deaf individuals. The notion that spatial selective attention plays a key role in modulating visual responses in the deaf has been recently advocated by Bavelier and colleagues (Bavelier et al., 2006; Dye et al., 2008) and originally stemmed from the empirical observation that differences between deaf individuals and hearing controls at the neural level has emerged specifically when attention was endogenously directed to the target (Bavelier et al., 2000; Neville and Lawson, 1987). In addition, this notion has been supported by evidence showing that, in deaf individuals, peripheral task-irrelevant distractors interact with shape discrimination more than central distractors, whereas the opposite pattern is observed in hearing controls (Proksch and Bavelier, 2002). Finally, a role of spatial attention has been suggested in those studies that examined attention orienting and revealed faster disengagement and re-orienting to the target after an invalid cue (Bosworth and Dobkins, 2002; Chen et al., 2006; Colmenero et al., 2004; Parasnis and Samar, 1985).

However, whether all aspects of visual enhancement in the deaf are necessarily linked to allocation of selective attention in space is still a matter of debate. At least under some circumstances enhanced visual performance in the deaf has been observed in the absence of attention orienting (Armstrong et al., 2002; Chen et al., 2006; Loke and Song, 1991). Thus, assessing the role of attention is fundamental to highlight at which stage of visual processing the performance benefit of deaf individuals could emerge. In particular, showing that enhanced processing emerge prior to orienting of attention would reveal that at least some components of enhanced processing in deaf individuals occurs at very early stages of visual processing in the brain.

1.5. The present study

In the present study, we examined directly whether orienting of spatial attention is a crucial determinant of enhanced visual processing in deaf individuals, by using two different speeded tasks: a simple detection task and a shape discrimination task, performed exactly on the same visual stimuli. The critical difference between these two tasks is that simple detection can be solved under distributed attention (i.e., without any orienting of spatial attention), whereas shape discrimination requires orienting of visual attention to the target, for localisation and identification (e.g., Bravo and Nakayama, 1992; Turatto et al., 2007; Sagi and Julesz, 1987).

The different role of attention orienting in detection and discrimination tasks is clearly illustrated by the classic study of Bravo and Nakayama (1992). Participants in that study were required to detect or discriminate a single target presented among multiple distractors. Both target and distractors were diamond shapes, with either the right or the left corner cut off. However, the target was identified by its colour difference with respect to the distractors (e.g., red target among green distractors). When target and distractors reversed their colour unpredictably from trial to trial, a clear performance difference between detection and discrimination tasks emerged as a function of number of distractors. Response time for simple target detection remained constant regardless of number of distractors; by contrast, response time for target shape discrimination decreased as number of distractors increased. The classic interpretation of this result (Bravo and Nakayama, 1992; Turatto et al., 2007; see also Sagi and Julesz, 1987) is that simple detection can be performed under distributed attention (i.e, can operate in parallel and therefore is unaffected by number of distractors), whereas shape discrimination can only occur after focused attention has been oriented to the target (therefore it is influenced by the number of distractors). Note that orienting of attention to a target becomes easier as the number of coherent distractors increase, because higher density of similar elements (distractors) make the target more salient and the selection process by focal attention faster (e.g., Sagi and Julesz, 1984).

In the present study, we tested a group of profoundly deaf individuals and a group of hearing controls in a simple detection task and in a shape discrimination task, to specifically evaluate whether orienting of focal attention is a necessary condition for observing supranormal visual ability in deaf individuals. If enhanced reactivity to visual events in deaf individuals reflects more efficient and fast orienting of selective attention to the target, faster responses in deaf than hearing participants should emerge more strongly in the shape discrimination than the simple detection task. By contrast, if orienting of visual attention is not critical for enhanced reactivity to emerge, any supra normal ability in this population should emerge in the simple detection task as well. It should be emphasised that a direct contrast of these two simple visual paradigms has not been conducted before in the literature on visual abilities of deaf individuals. In fact, to our knowledge, only one study in this literature has adopted a simple visual detection task, performed in the absence of any previous cue to orient the participant's spatial attention (Loke and Song, 1991; we will return to this pioneering study in detail in the Discussion).

Intriguingly, one simple detection study in the deaf conducted in the tactile modality (Levänen and Hamdorf, 2001) have suggested that deaf can outperform hearing controls when the task requires a response to rare tactile-frequency changes (i.e., deviants), embedded into a stream of stimuli of homogenous tactile frequency (i.e., standards). This latter supra-normal ability of deaf individuals in detecting tactile deviants, is somewhat analogue to the well-known ability of hearing individuals to detect pre-attentively an auditory deviants among auditory standards (e.g., Näätänen et al., 2001), suggesting that enhanced detection of tactile deviants in deaf individuals might depend upon the recruitment of auditory structures normally devoted to the processing auditory deviants (Levänen et al., 1998).

Thus, as secondary aim of the present study, we examined whether enhanced detection of non-auditory deviants in deaf individuals could also emerge in the visual modality. To this aim, we manipulated the interstimulus interval (ISI) between the warning signal at trial onset and target appearance. Specifically, 86% of the visual targets were delivered in a temporal window between 400 and 800 ms from the warning signal (standard trials), whereas the remaining 14% of the visual targets were delivered 1800 ms after the warning signal (deviant trials). A similar probability manipulation of temporal onset of visual targets have been previously conducted by Neville and colleagues (1983), and was chosen here under the assumption that timing is a critical feature of the auditory modality and thus any enhanced detection of visual deviants in deaf individuals should emerge more strongly through a probability manipulation of this specific task dimension.

2. Methods

2.1. Participants

Eleven profoundly deaf individuals (mean age = 26 years, SE = 1, range 21–34 years old; 8 males and 3 female) were recruited at the Italian national association for deaf (Ente Nazionale per la protezione e assistenza dei Sordi, Verona, Italy) and gave their informed consent to participate in the study. All participants had uncorrected bilateral profound hearing loss (> 80 dB). Two acquired deafness around the age of 4, 7 acquired deafness before the age of 3, and 2 had congenital deafness. All deaf participants were proficient sign-language users.

Eleven hearing controls (mean age = 28 years, SE = 1, range 24–32 years old; 5 males, 6 females) were also recruited to take part in the study. All hearing controls were recruited among the students at the Faculty of Cognitive Science (University of Trento). All participants had normal or corrected-to-normal vision and were right-handed by self-report. The study was approved by the ethical committee at the University of Trento (Italy).

2.2. Stimuli and apparatus

All stimuli were presented on a standard 17 inches monitor, with 1024 X 768 pixel resolution. The experiment was programmed with E-Studio 1.1.4.1, and controlled with E-Prime 1.1.4.1 (http://www.pstnet.com/products/e-prime).

Visual fixation was a small white cross (approximately 1 degree of visual angle), presented at the centre of the screen throughout the trial. The target was always a circle, opened on the left or right side and could be presented at one of 8 possible locations arranged on two invisible concentric circles centred on visual fixation. The radius of the inner circle was 3 degrees of visual angle, and the radius of the outer circle was 8 degrees of visual angle. There were 4 possible target locations on the inner circle and 4 possible target locations on the outer circle, placed along the two diagonals of the display. From now on we will refer to locations on the inner circle as central, and locations on the outer circle as peripheral. Target appearing at peripheral locations were corrected for the cortical magnification factor (Saarinen et al., 1989). Central targets covered a visual angle of 1.5 degrees and peripheral target of 2.6 degrees.

All possible target locations are indicated by dotted circles in Fig. 1 for descriptive purpose only (i.e., no circle was present on the actual experimental display). This figure also shows one representative central target (circle open on the left side) and one representative peripheral target (circle open on the right side). Again, this is only for descriptive purposes, as a single target was presented in every trial.

2.3. Procedure and design

Participants sat at approximately 60 cm from the computer monitor, resting their chest on the edge of the table, and were instructed to keep their head and eyes oriented towards fixation throughout testing. These instructions were repeated at the beginning of each experimental block, in addition the experimenter always remained in the room during testing to check that participants complied with the eye-head posture instructions. The flickering fixation was introduced precisely with the purpose of attracting the participant's attention to the centre of the visual scene at the beginning of each trial.

The experimental session always comprised two parts: a simple detection task (lasting approximately 20 minutes) and a shape discrimination task (lasting ap-

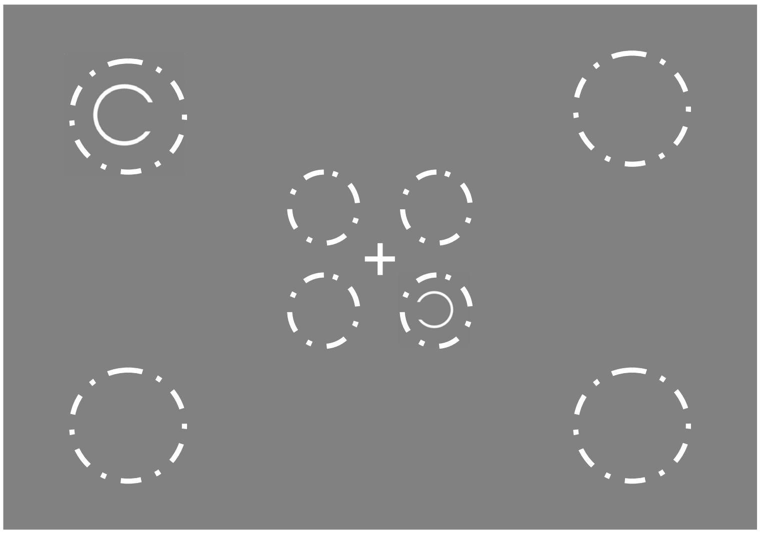


Fig. 1. All possible target locations are indicated by dotted circles; this serves only descriptive purpose as no circle was present on the actual experimental display. The figure also shows one representative central target (circle open on the left side) and one representative peripheral target (circle open on the right side). Again, this is only for descriptive purposes, as a single target was presented in every trial (see text for details).

proximately 30 minutes). In the simple detection task, participants were asked to respond as fast as possible to the sudden onset of the visual target, by pressing the space bar on the computer keyboard. In the shape discrimination task, participants were asked to make speeded discrimination of the target shape. Namely, they were instructed to press the 'B' key when the target circle was opened on the left side, and the 'N' key when the target circle was opened on the right side.

Each trial began with visual fixation flickering at 5Hz for 600 ms. This manipulation had the purpose of capturing the participant's attention and gaze towards the centre of the screen. After flickering, fixation remained still for a random interval ranging between 400 and 2200 ms, then a single visual target appeared at one of the 8 possible locations (i.e., 4 central and 4 peripheral) for 48 ms. As anticipated in the Introduction, one side aim of the present study was to assess whether detection and discrimination abilities of deaf and hearing participants could be influenced by a probability manipulation of target occurrence. To this aim, on 84% of the trials the target stimulus appeared in a time-window between 400 and 800 ms after fixation stopped flickering (standard trials); whereas on the remaining 16% of the trials the target appeared exactly 1800 ms after the end of fixation flickering (deviant trials; see Neville et al., 1983 for a similar manipulation). Deviant trials only occurred after three consecutive standards trials. The participant's response terminated the trial, and a random inter-trial interval ranging between 1250 and 1750 ms was introduced before the beginning of the subsequent trial. In case of anticipation responses or errors in the shape discrimination task, a warning sentence was delivered at fixation ('Early response' or 'Wrong response', respectively).

The simple detection task and the shape discrimination task comprised a total of 256 trials each. Trials were evenly distributed across the 8 possible target locations, resulting in 128 central trials, and 128 peripheral trials. Also, within each task 192 trials were standards and 32 were deviants. The 256 trials were always divided into two blocks and was preceded by 16 practice trials which were not analysed. The experiment was a 2 by 2 by 2 factorial design, with target location (central or peripheral) and trial type (standard or deviant) as within-participants factors, and group (deaf or hearing controls) as between-participant factor. In the simple detection task, the only dependent variable was the response time (RT). In the discrimination task, both RTs and accuracy were examined.

3. Results

3.1. *Simple detection task*

Data of one deaf participant were eliminated from the analysis of the simple detection task because his mean response times were more than 3 standard deviations above the deaf sample mean. Median simple

Table 1
Mean Reaction Times with standard errors in parenthesis for each experimental group as a function of target location and trial type

Simple detection task				
	Central		Peripheral	
	Standard	Deviant	Standard	Deviant
Hearing controls	261 (12)	261 (8)	265 (11)	268 (9)
Deaf individuals	207 (3)	231 (6)	206 (4)	235 (6)

RTs in response to visual targets were computed for each participant at each target location and entered into a mixed Analysis of Variance (ANOVA) with target location (central or peripheral) and trial type (standard and deviant) as within-participants factor, and group (deaf or hearing controls) as between-participant factor. Overall group performance is reported below and in Table 1 as means of medians.

This analysis revealed a significant main effect of target location (F(1,19) = 10.3, $p < 0.005$, hp$^2 = 0.35$), caused by faster responses to central (mean = 240 ms, SE = 5) than peripheral targets (mean = 244 ms, SE = 5) overall. In addition, there was a main effect of trial type (F(1,19) = 8.7, $p < 0.008$, hp$^2 = 0.31$), caused by faster responses to standard (mean = 235, SE = 7) than deviant targets (mean = 249, SE = 5). More importantly for the purpose of the present study, there was also a main effect of group (F(1,19) = 17.3, $p < 0.001$, hp$^2 = 0.48$). Deaf participants were on average 44 ms faster than hearing controls at detecting the visual targets (mean = 220 ms, SE = 7; vs. mean = 264 ms, SE = 8, respectively; see Fig. 2a). The interaction between group and trial type was also significant (F(1,19) = 7.1, $p < 0.015$, hp$^2 = 0.27$). Although deaf participants were faster than hearing controls regardless of trial type ($p < 0.008$), RTs in the deaf were faster for standard than deviant targets (206 ms vs. 233 ms, respectively; t(9) = 4,6, $p < 0.001$) unlike hearing controls (263 ms vs. 264 ms; t(10) = 0.2, n.s.). Finally, the interaction between group and target location also approached significance (F(2,19) = 3.5, $p < 0.08$, hp$^2 = 0.16$). No other interaction reached significance ($F < 2.1$).

To further evaluate the interaction between group and target location we run an additional analysis on RTs in standard trials only. This was motivated by the large trial difference between standard and deviant conditions: with 96 trials for each target locations in standard trials and only 16 trials for target location in deviant trials. Median simple RTs in response to the standard target alone were entered into a mixed ANOVA with target location (central or peripheral) and group (deaf or hearing controls) as factors. This analysis confirmed a main effect of group (F(1,19) = 9.8, $p < 0.001$, hp$^2 = 0.52$), caused by deaf participants responding on average 57 ms faster than hearing controls (mean = 206 ms, SE = 9; vs. mean = 263 ms, SE = 9, respectively). In addition, the interaction between the group and target location was now significant (F(2,19) = 4.5, $p < 0.05$, hp$^2 = 0.2$). Although deaf were faster than hearing controls regardless of target location ($p < 0.0001$), a significant cost of responding to peripheral than central targets emerged for hearing controls (central: mean = 261, SE = 9; peripheral: 265, SE = 8.6; t(10) = 2.3, $p < 0.05$), but not for deaf participants (central: mean = 207 ms, SE = 9; peripheral: mean = 206, SE = 9; t(9) = 0.7, n.s.).

In sum, when standard trials are analysed separately, it becomes evident that deaf participants do not pay any cost in terms of RTs when reacting to peripheral than central targets, unlike hearing controls. Perhaps more strikingly, in both analyses deaf proved substantially faster than hearing controls overall, revealing an enhancement of visual processing which does not selectively emerge for targets presented at the periphery of the visual field.

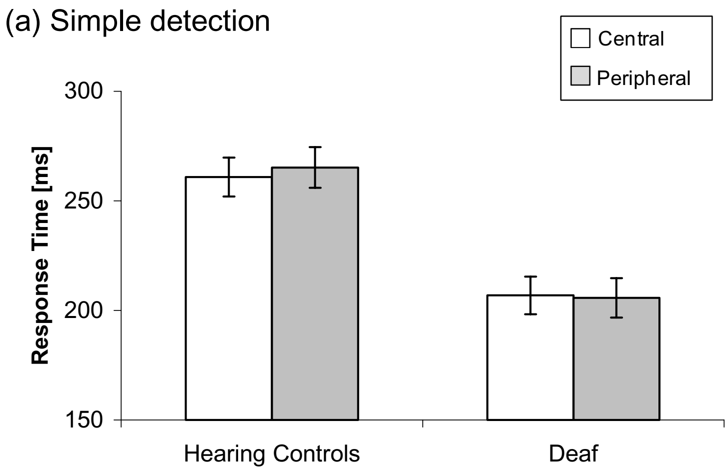
3.2. *Shape discrimination task*

Median RTs for correct discrimination trials and percentage of errors were entered separately into a mixed ANOVA with target location (central or peripheral) and trial type (standard or deviant) as within-participants factors, as well as group (deaf or hearing controls) as between-participant factor. As before, overall group performance is reported below and in Table 2 as means of medians.

The analysis on RTs for correct discrimination trials revealed a main effect of target location (F(1,20) = 15.02, $p < 0.001$, hp$^2 = 0.43$), indicating that all participants were faster at discriminating central (mean = 423 ms, SE = 11) than peripheral targets (mean = 439 ms, SE = 12). The main effect trial type was also significant (F(1,20) = 39.8, $p < 0.0001$, hp$^2 = 0.66$), caused by faster discriminations for standard (mean = 421 ms, SE = 11) than deviant targets (mean = 442 ms, SE = 12). Importantly, the main effect of group did

Table 2
Mean Reaction Times and mean percent errors with standard errors in parenthesis for each experimental group as a function of target location and trial type

Shape discrimination task				
	Central		Peripheral	
	Standard	Deviant	Standard	Deviant
Hearing controls				
Response time	378 (16)	392 (17)	390 (18)	413 (21)
Percent errors	2% (1%)	2% (2%)	3% (2%)	3% (2%)
Deaf individuals				
Response time	349 (13)	377 (14)	366 (15)	386 (15)
Percent errors	5% (2%)	5% (2%)	5% (2%)	8% (2%)


(a) Simple detection

(b) Shape discrimination

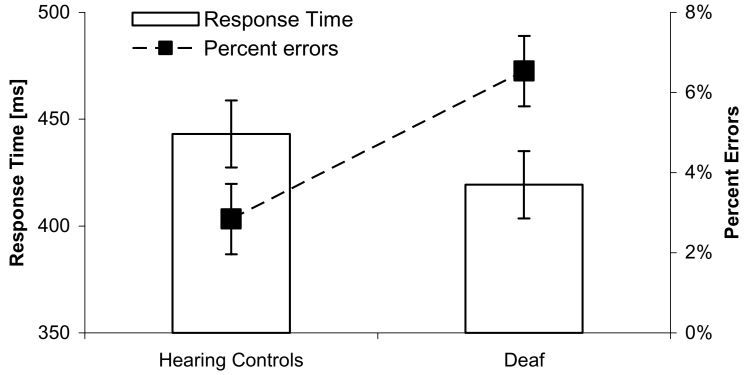


Fig. 2. Performance of deaf participants and hearing controls (a) in the simple detection task as a function of target locations; (b) in the shape discrimination task, both in terms of response time and percent errors; note that in the shape discrimination task performance in the two groups was not modulated by target location, therefore this is not illustrated in the plot (but see Table 2 for means across all conditions). Error bars represent the Standard Error of the mean.

not reach the level of significance (F(1,20) $= 1.1$, $p < 0.3$, $\text{hp}^2 = 0.05$; see Fig. 2b). No other interaction was significant (all Fs < 1.3).

The analysis on percentage of errors in shape discrimination revealed a main effect of group (F(1,20) $=$ 4.8, $p < 0.05$, $\text{hp}^2 = 0.2$); surprisingly, however, this main effect revealed that deaf participants performed worse than hearing controls (mean $=$ 6%, SE $=$ 1%;

mean = 3%, SE = 1%, respectively; see Fig. 2b). No other main effect or interaction was significant (all Fs < 1.6).

As for the simple detection task, we repeated all analyses on standard trials considered alone using a mixed ANOVA design with target location (central or peripheral) and group (deaf, hearing controls) as factors. The analysis on RTs confirmed a main effect of target location (F(1,20) = 11.6, $p < 0.003$; $hp^2 = 0.37$), caused by faster discrimination responses for central (mean = 413 ms, SE = 10) than peripheral targets (mean = 428 ms, SE = 12). No other main effect or interaction reached significance (all Fs < 1.5). The analysis on percent errors confirmed the main effect of group (F(1,20) = 8.9, $p < 0.01$, $hp^2 = 0.3$) caused by deaf participants performing worse than hearing controls overall (mean = 7%, SE = 1%; mean = 2%, SE = 1%, respectively). No other main effect or interaction was significant (all Fs < 1.6).

In sum, the results of the discrimination task revealed no between-group differences in terms of RTs. However, discrimination performance was significantly worse in deaf individuals than hearing controls.

4. Discussion

The aim of the present study was to assess whether faster reactivity to visual events in the profoundly deaf is strictly dependent upon orienting of selective spatial attention. To this aim we compared reactivity in deaf and hearing participants in response to identical visual stimuli appearing at central or peripheral locations, when the task requires a simple detection and when it requires a shape discrimination. Because simple detection does not need target localisation and identification it is usually assumed to occur without orienting of spatial attention (i.e., under distributed attention; Bravo and Nakayama 1992; Sagi and Julesz, 1987; Turatto et al., 2007). By contrast, shape discrimination can only be performed after attention has been oriented to the stimulus.

The results of the present study clearly revealed a response time advantage in deaf than hearing participants, which emerged selectively for the simple detection but not for the shape discrimination task. While in the simple detection task deaf individuals outperformed hearing controls by 44 ms (i.e., a 17% reduction of response time, when compared with the average RT of hearing controls; mean = 264 ms), in the shape discrimination task neither response time nor accuracy was better in deaf than hearing participants. In fact, deaf participants made significantly more errors than hearing controls.[2] Notably, faster responses in deaf individuals during the simple detection task were not spatially selective, i.e., they emerged regardless of target location, instead of appearing only for peripheral targets (Loke and Song, 1991). This finding is even more striking when considered within the context of differential response time ratios in the two groups as a function of target location. Hearing controls paid a significant RT cost for peripheral than central target, whereas deaf individuals performed comparably well across the two target locations. Thus, in addition to replicating the well-known enhancement of peripheral processing in the deaf, our finding reveals that the reactivity enhancement in deaf individuals cannot be reduced to better peripheral processing alone.

These findings raise the possibility of two functionally distinct aspects in the reorganisation plasticity occurring in the visual system of the profoundly deaf. One the one hand, the observation that deaf were faster than hearing controls in a task that does not require any orienting of attention prior to the response (i.e., simple detection) implies a functional enhancement which is not dependent upon movements of visual attention in external space. Importantly, this aspect of compensatory plasticity extends to central as well as peripheral locations of the visual field, instead of emerging selectively for peripheral items. One the other hand, the observation that profoundly deaf individuals show no RT cost when processing peripheral items, even in a simple detection task that can be solved under distributed attention, implies a functional enhancement for peripheral portions of the visual field that cannot be reduced to differential allocation of attentional resources alone (see also Stevens and Neville, 2006 for related evidence). Because the cost for processing peripheral than central targets in hearing controls likely reflects the amount of visual neurons devoted to the analysis of central than peripheral portion of the visual field (which would result in shorter RTs according to a horse-race model of response release; e.g., see Marzi and Di Stefano, 1981; Chelazzi et al., 1988), we speculate that

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[2] As can be noted from Fig. 2b the worse performance of deaf participants was accompanied by a numerical trend for shorter RTs in deaf than hearing controls. This difference was statistically not significant and therefore will not be discussed further in the manuscript. However, it should noted that a tendency towards speed accuracy trade-off has already been documented in the literature on visual abilities of the deaf (e.g., Bosworth and Dobkins, 2002).

profound deafness can modify the relative proportion of neurons devoted to peripheral processing or their baseline activity. Before discussing further the possible mechanisms that have led to enhanced reactivity of the deaf in the simple detection task, we will examine in more detail the previous evidence on speeded detection and speeded discrimination in the profoundly deaf.

4.1. *Speeded detection to visual targets*

The evidence that deaf individuals show faster detection response time to static visual targets regardless of attentional instructions, was documented by Chen and colleagues (Chen et al., 2006) for targets appearing at para-foveal eccentricities (i.e., 3 degrees; the same eccentricity used in the present study for central visual targets). In their study, regardless of whether the target appeared at spatially valid or invalid cued locations, deaf responded on average 59 ms faster than hearing controls (but see Parasnis and Samar, 1985). Similarly, speeded responses to static targets at peripheral eccentricities (i.e., 20 degrees) were examined by Colmenero and colleagues (Colmenero, et al., 2004) in a task in which targets were always preceded by a cue that was either spatially valid, invalid or neutral. Regardless of cue validity, deaf resulted on average 43 ms faster than hearing controls. Remarkably, only one study (Loke and Song, 1991) has contrasted directly central and peripheral locations (at 0.5° or 25° of visual angle respectively), during a speeded detection task performed in the absence of any attention orienting cue. Based on the average of only 10 trials for each target location, they documented statistically faster responses for deaf than hearing controls for peripheral targets. Intriguingly, a similar between-group difference was also numerically evident for central locations (38 ms on average Loke and Song, 1991, see p. 439).

The latter study particularly contributed to the shared assumption that speeded responses in the profoundly deaf are faster only for peripheral locations (e.g., Bavelier et al., 2006). However, the novel empirical evidence of the present study, as well as other existing evidence from previous works on speeded detection (Bottari et al., under review; Chen et al., 2006; Colmenero et al., 2004), call for a re-definition of this general assumption. First, deaf enhanced reactivity to static visual targets can occur irrespective of target eccentricity. Second, it does not depend entirely upon allocation of attentional resources in the visual field.

4.2. *Speeded discrimination to visual targets*

To our knowledge, the only study that adopted a discrimination paradigm somewhat similar to ours is the pioneering work of Neville and Lawson (1987), in which deaf participants were asked to make a trial-by-trial motion-direction discrimination for single suprathreshold stimuli presented at central or peripheral locations (just above fixation vs. 18 degrees from fixation, respectively). In their study, deaf were faster than hearing controls at discriminating the direction of motion of peripheral targets (in the absence of accuracy differences between groups). This result is clearly at odds with the present observation of worse accuracy performance in deaf than hearing individuals, regardless of target eccentricity. Two aspects could however account for this discrepancy of results. First, our peripheral targets appeared at much less eccentric locations than those of Neville and Lawson (8 degrees vs. 18 degrees, respectively). This raises the possibility that any speed benefit related to attention shifts in discrimination tasks is more likely to emerge when large spatial attention shift are requested. Second, all our visual stimuli were static whereas those adopted by Neville and Lawson were moving. This raises the possibility that motion and static stimuli have a different status in the crossmodal plasticity phenomena that occur in deaf individuals.

4.3. *Which mechanisms can lead to enhanced reactivity in the simple detection task?*

An initial possibility is that faster responses to visual targets reflect sensory enhancement occurring in sub-cortical structures. Neuroanatomical studies in deaf mice have shown that several sub-cortical structures which are normally part of the auditory pathway can be recruited for visual processing. For example, aberrant projections from the retina have been found in the dorsal and ventral portion of the medial geniculate nucleus (MGL) of the thalamus and in the intermediate layers of the superior colliculus (SC; Hunt et al., 2005). If similar phenomena of sub-cortical plasticity occur in humans, this would lead to a redundancy of neurons dedicated to visual processing within subcortical neural structures known to enhance speed of response. For instance, it is now well-documented that faster detection responses occur with two concurrent sensory signals than one (the so-called ‘Redundant Signal Effect’). This effect is mediated by neural summation occurring in the SC (Savazzi and Marzi 2002), particularly in the magnocellular layers (Turatto et al., 2004). Intriguingly, this phenomenon has recently been documented also with audio-visual pairings (Leo et al., 2008; Maravita et al., 2008). Thus, it would be tempting to link speeded responses in our detection task with the recruitment for visual processing of sub-cortical structures originally devoted to auditory processing.

A second possibility is that faster responses in the deaf reflect some aspect of response preparation or release. Simple detection tasks allow response selection and response programming before target presentation. Therefore, only a response release is needed following the target stimulus. This is clearly illustrated by the fact that in simple detection tasks, unlike choice RT tasks, response times do not increase when response complexity increases (Klapp, 1995). Thus, reactivity effects observed in profoundly deaf individuals could reflect, to some extent, a facilitated release of pre-programmed motor responses. Interestingly, this may again reflect a re-organisation occurring subcortically, because there is evidence that response release in simple detection tasks may be mediated by sub-cortical structures (Carlsen et al., 2004). This interpretation of our findings would account well for the speed-accuracy trade-offs occasionally noted in deaf individuals (e.g., Bosworth and Dobkins, 2002; see also Footnote 2), as facilitated response release could lead to delivery of the wrong response.

Finally, it can be hypothesised that enhanced response speed in deaf individuals reflect changes occurring at the cortical level. In this respect, it is known from EEG studies that latencies in the response to visual targets co-varies with latencies in peaks recorded from occipital electrodes (Fort et al., 2005; Hartwell and Cowan, 1994). This lead to the strong prediction that fast RTs in the deaf should correspond to early activation peaks in cortical responses of deaf individuals compared to hearing controls. To date, however, such evidence have never been reported. The ERP study by Neville and Lawson (1987), that showed a 70 ms RT difference between deaf and hearing controls at the behavioural level, showed no difference between the two groups in terms of neural latencies (see also Neville et al., 1983). Instead, between-group differences have been documented on the amplitude of the N1 component (Armstrong et al., 2002; Neville and Lawson, 1987). Although this negative finding should be taken with caution, it argues against a cortical origin of the substantial reactivity effect we have observed.

4.4. Different performance for standard and deviant targets

The secondary aim of the present study was to assess whether any difference between deaf individuals and hearing controls could also emerge in relation to the probability of occurrence of visual stimuli. To this aim, we manipulated the temporal onset probability of our visual targets (i.e., standard targets were delivered between 400 and 800 ms after warning at fixation, whereas deviant targets were delivered 1800 ms after warning at fixation). Results showed that deaf participants were slower at detecting deviant than standard targets, unlike hearing controls who did not show a different performance for standard and deviant targets. We briefly discuss this finding for completeness. However, because the target probability manipulation was confounded with the different timing of the stimuli, we believe that any conclusion on the ability of deaf and hearing individuals to detects visual deviants is problematic and inconclusive at this stage. Slower detection for deviant visual targets in deaf participants could have emerged in our study as a result of the probability manipulation, as a result of the longer timing of the deviant trials, or due to the combination of these two factors. In particular, one recent work from our lab (Bottari et al., in preparation) in which visual targets were presented at short or long ISI (as here) but with equal probability (i.e., 50% short ISI trials and 50% long ISI trials) revealed that deaf individuals display a reactivity advantage compared to hearing controls particularly when the visual target is presented at short latencies from the warning signal. We are now investigating further whether a manipulation that affects percentage of occurrence of visual events can modulate differently the performance of deaf and hearing individuals.

4.5. Conclusions

Taken together the results of the present study provide clear evidence that enhanced reactivity to visual stimuli in the deaf cannot be explained by faster orienting of attention alone. Moreover, we show that this performance enhancement can emerge for central as well as peripheral eccentricities. However, we also show that while hearing controls paid a cost in responding to peripheral than central targets, deaf participants performed equally well at both target locations. This peripheral advantage, observed here under distributed attention in the simple detection task, suggests that the spatially-selective effect in the deaf could result from reorganised sensory processing rather than different attentional gradients.

Acknowledgements

We are grateful to the deaf at the Ente Nazionale Sordi (Verona) who generously volunteered their time in this study. F.P. was supported by a PRIN 2006 grant (Prot. 2006118540_004) from MIUR (Italy), a grant from Comune di Rovereto (Italy) and a PAT-CRS grant from University of Trento (Italy).

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