

Response speed advantage for vision does not extend to touch in early deaf adults

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Abstract Early deaf adults typically respond faster than hearing controls when performing a speeded simple detection on visual targets. Whether this response time advantage can generalise to another intact modality (touch) or it is instead specific to visual processing remained unexplored. We tested eight early deaf adults and twelve hearing controls in a simple detection task, with visual or tactile targets delivered on the arms and occupying the same locations in external space. Catch trials were included in the experimental paradigm. Results revealed a response time advantage in deaf adults compared to hearing controls, selectively for visual targets. This advantage did not extend to touch. The number of anticipation errors was negligible and comparable in both groups. The present findings strengthen the notion that response time advantage in deaf adults emerges as a consequence of changes specific to visual processing. They also exclude the involvement of sensory-unspecific cognitive mechanisms in this improvement (e.g. increased impulsivity in initiation of response, longer-lasting sustained attention or higher motivation to perform the task). Finally, they provide initial evidence that the intact sensory modalities can reorganise independently from each other following early auditory deprivation.

Keywords Bilateral deafness · Plasticity · Reaction time · Vision · Touch

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Introduction

Despite living in a world without sounds, deaf adults typically interact efficiently with their surrounding environment. The behavioural advantages and the changes in brain response that contribute to this adaptive outcome have been the focus of many investigations in the last three decades (for reviews see Bavelier et al. 2006; Pavani and Röder 2012). These studies have primarily examined visual processing in deaf adults but in more recent years also somatosensory processing (e.g. Auer et al. 2007; Bolognini et al. 2012; Frenzel et al. 2012; Heming and Brown 2005; Levänen et al. 1998; Levänen and Hamdorf 2001; Moallem et al. 2010; van Dijk et al. 2013) and visuotactile interactions (Karns et al. 2012) have been considered.

One repeatedly documented behavioural advantage in deaf adults compared to hearing controls is the faster response time measured when the task requires simple detection of visual onsets (see Pavani and Bottari 2012 for review). Loke and Song (1991) were the first to describe this behavioural advantage in a group of congenitally deaf adults using simple detection. Deaf participants were faster (85 ms on average) than hearing controls at detecting asterisks presented briefly at 25 degrees of visual eccentricity. This pioneering study observed that a similar advantage did not emerge when stimuli were presented closer to central fixation. However, subsequent works have challenged this conclusion by showing response speed advantage in early deaf adults also for visual stimuli delivered directly at fixation (Reynolds 1993) or at peri-foveal locations (Bottari et al. 2010; 2011; for a meta-analysis of response speed advantage in deaf compared to hearing adults as a function of visual target eccentricity see Figure 22.1 in Pavani and Bottari 2012).

It is currently unknown whether the response speed advantage documented for vision also extends to the intact tactile modality. Despite the increasing interest for changes in somatosensory processing following deafness, behavioural responses to tactile events have never been investigated using reaction time measures (e.g. Bolognini et al. 2012; Frenzel et al. 2012; Heming and Brown 2005; Levänen and Hamdorf 2001; Moallem et al. 2010; van Dijk et al. 2013). The most intuitive prediction would be that a response time advantage similar to the one observed for visual stimuli should emerge for tactile processing as well. This is because response speed advantages in the deaf population have been interpreted as the consequence of *sensory-unspecific* changes related to the motor response phase and have been associated with increased impulsivity in initiation of response (Parasnis et al. 2003). More generally, a number of sensory-unspecific processes are involved in speeded simple detection. These include perceptual decision-making, response preparation and initiation, in addition to sustained or selective attention abilities and motivation in performing the task.

However, one recent study suggests that response speed advantage in deaf adults might actually reflect *sensory specific*—rather than unspecific—changes that may primarily involve early processing of the visual stimulus. Using electroencephalography (EEG), Bottari et al. (2011) explored the relationship between speeded visual detection and the temporal dynamic of visual processing in the brain of deaf and hearing individuals. They recorded EEG while deaf and hearing participants performed a simple detection task on visual stimuli delivered at peri-foveal or peripheral visual locations and in response to a warning visual signal that preceded the targets. Differences between the two groups were measured for the C1 component (i.e. a visual evoked potential produced by the striate cortex, with a peak around 80 ms post-stimulus) and for the P1 component (i.e. another early component of visual processing, peaking between 100 and 130 ms post-stimulus). Most importantly, a significant correlation between the amplitude of the P1 component and the response time advantage emerged selectively for the deaf group. The shorter the average response times to the visual events the ampler the P1, independently of stimulus eccentricity. This led Bottari et al. (2011) to propose that faster response times to visual stimuli in deaf adults reflect early changes in the temporal dynamic of visual processing and may thus be linked to specific modifications occurring within the visual system.

In the present study, we aimed to further understand the origin of the response time advantage in deaf adults by introducing two straightforward manipulations. First, we examined whether any advantage in response time for deaf compared to hearing adults emerges equally for vision and for touch. If response speed advantages result from specific

changes occurring within visual processing (as proposed by Bottari et al. 2011), no response speed advantage should be found when deaf participants react to tactile targets. By contrast, if response speed advantages reflect sensory-unspecific changes related to speeded detection, similar facilitation in response times should emerge regardless of target modality.

The second manipulation we introduced was the presence of catch trials (i.e. response release when no stimulus is presented) in the design, paired with an analysis of anticipated responses (i.e. response release before any stimulus has been delivered). Surprisingly, all previous studies on simple detection in deaf adults (Bottari et al. 2010, 2011; Chen et al. 2006; Colmenero et al. 2004; Loke and Song 1991; Reynolds 1993) did not include catch trials in the experimental design. If the advantage in reaction times to visual events in the deaf population depends on increased impulsivity in initiation of response, we should observe a higher proportion of erroneous responses to catch trials and higher proportion of anticipated responses in this population compared to hearing controls.

We tested a group of deaf adults and a group of hearing controls in a simple detection task with visual or tactile stimuli, delivered at central or peripheral locations. To match as closely as possible central and peripheral locations across the two modalities, we delivered tactile stimuli on the arms (fingertip or forearm) and aligned central and peripheral visual stimuli with the tactile locations (see Fig. 1a). For exploratory purposes, we additionally introduced tactile stimulations to a bodily region inaccessible to vision, i.e. the back of the neck (see Fig. 1b), in deaf participants only.

Unlike stimuli approaching from the front, which are typically visible before they touch the skin and can therefore be anticipated, stimuli at the back of the head are always abrupt for deaf people. They cannot be anticipated in any ways in deaf individuals, whereas they are often anticipated through audition in people with normal hearing. For this reason, we hypothesised that they might trigger faster reactions in deaf compared to hearing participants. This latter manipulation was conducted only in deaf participants because, due to the characteristic of the available vibrotactile apparatus, it could not be applied in hearing controls without producing mixed tactile and auditory stimulation.

Methods

Participants

Twelve hearing participants (mean age = 28.6 years old, SD = 2.7) and eight early deaf participants (mean

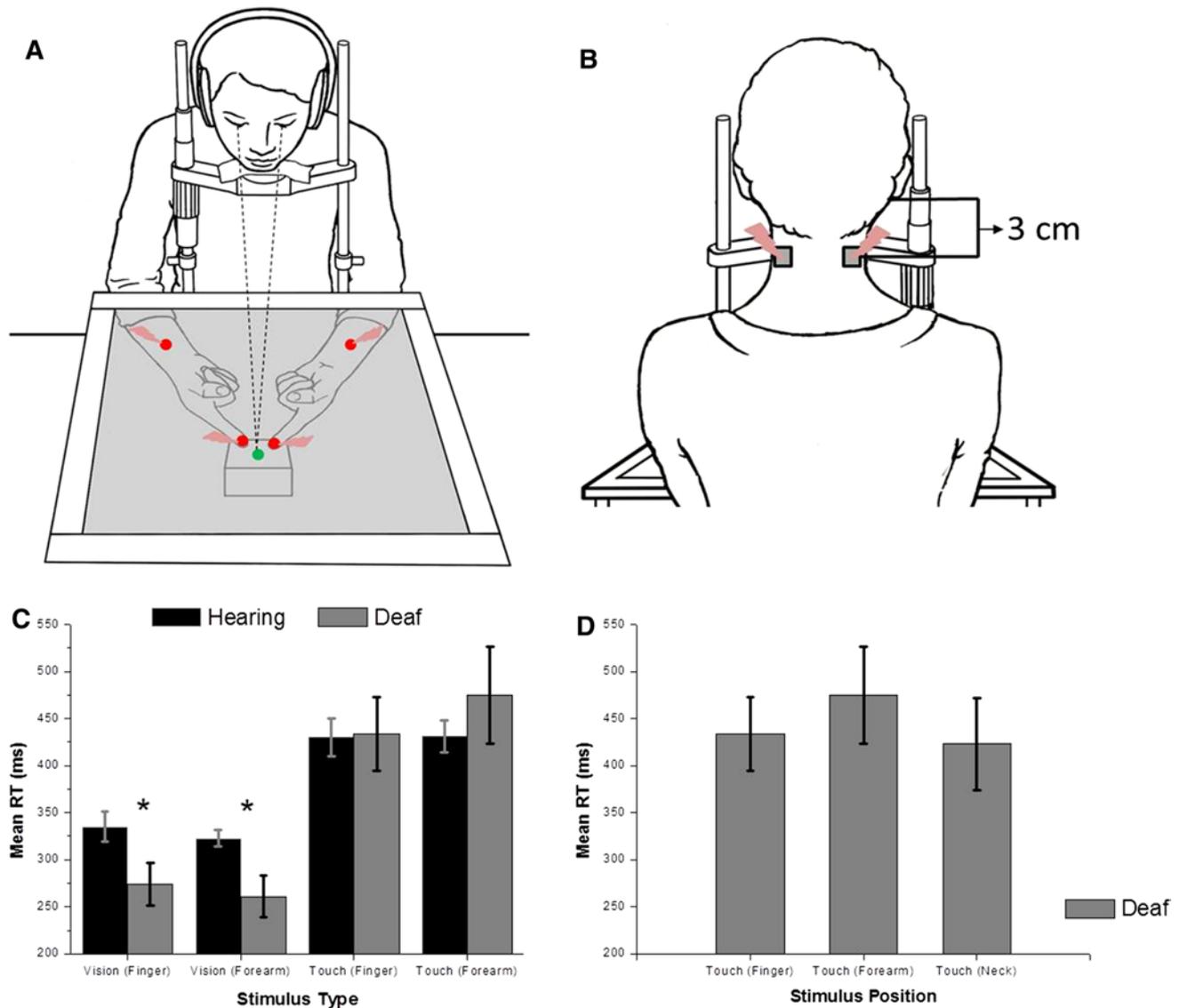


Fig. 1 **a** Experimental set-up, participant's posture and location of visual and tactile stimuli, identified by *circles* or *sparkles* on the arms, respectively. **b** Experimental set-up showing tactile stimulus positions in the back of the neck. **c** Results (modality \times group interaction). For visual targets, deaf participants (mean RTs = 267 ms, SE = 22), were significantly faster than hearing controls (mean

RTs = 329 ms, SE = 12). For tactile targets, deaf and hearing participants did not differ between each other (deaf: mean RTs = 454 ms, SE = 44; hearing: mean RTs = 431 ms, SE = 18). **d** Results. Deaf participants showed no difference in RTs across the three tactile positions tested (fingertip: mean RTs = 434 ms, SE = 38.7; forearm: 475 ms, SE = 51.3; neck: 423 ms, SE = 49)

age = 34.2 years old, SD = 5.5) took part in the experiment. Table 1 reports detailed information for each deaf participant. None became deaf due to systemic causes that could also affect vision, and none was born from deaf parents nor received a cochlear implant. Six deaf participants knew and used Italian Sign Language, but none of them learned it as first language. No hearing participant was familiar with sign language. All participants reported to have normal or corrected-to-normal vision as well as normal somatosensation. No one reported to suffer from any psychiatric disorder or neurological disease.

The Ethical Committee of the University of Trento approved the study.

Stimuli and apparatus

Participants sat on a comfortable chair with their chin on a chin rest and their hands and forearms resting supine on a table. A wooden cube ($7 \times 7 \times 7$ cm) placed along the participant's midsagittal plane, at approximately 60 cm from the participant's chest, served as resting position for the index fingers. One green LED positioned on the wooden

Table 1 Anamnestic information for each deaf participant, collected through a brief questionnaire completed prior to the experiment

Deaf participant	Age (years)	Deafness			Sign language
		Onset	Degree	Aetiology	Age of acquisition (years)
1	33	2 months	Profound	Otitis	17
2	26	Birth	Profound	Congenital	20
3	31	Birth	Severe	Rubella	21
4	37	20 days	Profound	Heart surgery complications	Does not use it
5	37	Birth	Profound	Congenital	14
6	29	Birth	Profound	Congenital	8
7	43	Birth	Profound	Congenital	Does not use it
8	38	Birth	Profound	Congenital	7

For the variable ‘Degree of Deafness’, ‘Profound’ corresponds to a loss ≥ 81 dB in the better ear; ‘Severe’ corresponds to a loss ≥ 61 dB in the better ear

cube served as visual fixation. Four red LEDs and four bone vibrators (Oticon A, dimensions 1.5 cm \times 2.5 cm) were used to deliver visual and vibrotactile stimuli, respectively. Two pairs of LEDs and bone vibrators were placed on the index fingertips, and two pairs were placed on the forearms. This resulted in four spatially congruent locations for visual and tactile stimulation: (1) right index; (2) left index; (3) right forearm; (4) left forearm (see Fig. 1a). Note that with this arrangement, retinal eccentricity was perfectly matched for each pair of visual and tactile stimuli. Also, placing the stimuli on the index and forearms allowed testing simple detection in vision and touch for regions of high and low spatial acuity. Specifically, stimuli at the index fingers were delivered in a region of high spatial acuity for both vision (1° from fixation) and touch (fingertip); similarly, stimuli at the forearms were delivered in a region of low spatial acuity for both vision (32° from fixation) and touch (forearm).

An opaque glass, suspended 9 cm above the hands, prevented direct vision of the set-up. With this set-up, visual stimuli (flashes of lights) were visible as a projection on the opaque glass when the LEDs were switched on, and tactile stimuli were felt but not seen. Vision of the stimulated hands and forearms was prevented throughout. For exploratory purposes, deaf participants were also tested with bone vibrators positioned in the back of the neck, 3 cm behind the ear lobes on either side of the neck (Fig. 1b).

All stimuli were clearly supra-threshold: visual stimuli lasted 60 or 100 ms, whereas tactile stimuli lasted 5 or 25 ms. Hearing participants wore headphones delivering white noise, to prevent any sound related to the operation of the vibrotactile stimulators. The white noise volume was adjusted individually. An I/O-box attached to a portable PC was used for stimulus presentation and response registration. The experiment was programmed using MATLAB with Psychtoolbox extensions (Brainard 1997; Pelli 1997).

Experimental design and procedure

At the beginning of each trial, fixation was switched on. After a random interval lasting between 1,000 and 1,400 ms, one stimulus appeared, unpredictably at any of the four possible positions. Participants were instructed to keep central fixation throughout the experiment and to release as fast as possible a foot pedal positioned under the heel of the right foot every time they detected a stimulus. If no response was given within 2 s from the target offset, the next trial started automatically. Inter-trial interval lasted 1,500 ms during which fixation remained lit for 1,000 ms, and then, it was switched off for the remaining 500 ms.

The experiment comprised two blocks of 100 trials each. Target modality changed between experimental blocks, in counterbalanced order across participants. In each block, 80 % of the trials were stimulation trials (20 stimuli for each of the four possible locations), whereas the remaining 20 % were catch trials, in which no stimulus was presented. Deaf participants performed also an additional block (50 trials, 10 % of catch trials), with tactile stimuli delivered in the back of the neck, which lasted less than 5 min.

All participants received written instructions. When needed, further clarifications were provided in spoken Italian or Italian Sign Language by the experimenter. All participants easily understood the task. In addition, before starting the experiment, all participants completed a brief practice (two blocks, one visual and one tactile, 10 trials each) to familiarise with the task.

Results

Trials in which reaction times (RTs) were faster than 100 ms or longer than 2,000 ms were excluded from the analysis. Importantly, the number of anticipations (i.e. RTs < 100 ms) and false alarms (i.e. responses to catch trials)

was negligible and comparable across the two experimental groups (deaf 0.2 %; hearing 0.1 %).

Median RTs for each participant were entered into a mixed ANOVA with modality (vision, touch) and target position (peri-foveal/fingertip, peripheral/forearm) as within-participants variables and group (deaf, hearing) as between-participants variable. This analysis showed a main effect of modality, caused by faster responses to visual compared to tactile stimuli overall [$F(1,18) = 60.9$, $p < 0.0001$, $\eta_p^2 = 0.77$]. The interaction between modality and target position also reached significance [$F(1,18) = 5.23$, $p = 0.03$, $\eta_p^2 = 0.23$], showing that both groups were faster when detecting peripheral (298 ms, SE = 12) than peri-foveal visual targets (310 ms, SE = 15), while the opposite was true for tactile targets (fingertip 432 ms, SE = 19; forearm 449 ms, SE = 23).

Most importantly, there was a significant interaction between group and modality [$F(1,18) = 5.25$, $p = 0.03$, $\eta_p^2 = 0.23$; see Fig. 1c]. Planned comparisons conducted using *t* tests showed that when responding to visual stimuli, deaf participants were significantly faster than hearing controls, regardless of visual targets eccentricity [$t(1,18) = 2.69$, $p = 0.01$]. By contrast, when responding to tactile stimuli, there was no difference between groups [$t(1,18) = 0.56$, $p = 0.6$; see Fig. 1c legend for means and standard errors, as a function of condition and group]. No other main effects or interactions reached significance (all F s < 2.23).

To test whether a response time advantage in the tactile modality may emerge selectively for region inaccessible to vision, we separately conducted a within-group ANOVA, only for the deaf group, with tactile stimulus position as variable (fingertip, forearm, neck). The effect of tactile stimulus position did not reach significance [$F(2,14) = 1.3$, $p = 0.3$], meaning that deaf participants were equally fast in responding to tactile targets, irrespective of their spatial position (see Fig. 1d legend for means and standard errors).

Discussion

Since the pioneering work by Loke and Song (1991), faster simple detection of visual events have been repeatedly documented in deaf adults compared to hearing controls (Bottari et al. 2010, 2011; Reynolds 1993; see Pavani and Bottari 2012 for review). However, it remained an open issue to what extent this behavioural advantage could be specific for vision or could be related to more sensory-unspecific processes (e.g. increased impulsivity in initiation of response, longer-lasting sustained attention or higher motivation to perform the task). A critical contribution of sensory-unspecific changes predicted an extension of the response speed advantage also to another

intact sensory modality (hear, touch). The present findings reveal selective response speed advantage for the *visual* modality in deaf adults compared to hearing controls, but no reaction time advantage for tactile events. This dissociation emerged in the context of negligible anticipation errors and false alarms, despite the fact that tactile and visual targets occupied exactly the same locations in external space.

These findings strengthen the proposal that this response speed advantage in deaf adults may reflect early changes in the temporal dynamic of *visual* processing (Bottari et al. 2011), rather than changes occurring in other sensory-unspecific mechanisms involved in simple detection. In particular, these findings are not compatible with a role of perceptual decision-making, response preparation, response impulsivity, sustained attention or motivation in the response speed advantage of deaf adults. Response impulsivity in the deaf group should have led to more anticipations and false alarms, which was not the case, as both these aspects of performance were comparable and negligible between the two groups. Furthermore, differences in any of the aforementioned sensory-unspecific mechanisms should have produced response speed advantages for deaf participants in *both* vision and touch.

The visual specificity of this behavioural advantage is in line with other studies documenting changes in early stages of visual processing in the deaf population. Codina et al. (2011), showed that deaf participants could detect moving dots, proceeding from the periphery to the central visual field, at more peripheral locations compared to hearing controls (see also Buckley et al. 2010). By combining this behavioural measure with the analysis of the optic nerve structure obtained with optical coherence tomography (OCT), Codina et al. (2011) also found that deaf participants (compared to hearing controls) had significantly larger neural rim areas within the head of the optic nerve (a non-invasive indicator of the numbers of retinal ganglion cells). Most strikingly, this measure of retinal reorganisation correlated with the extension of the visual field as measured by the behavioural task, revealing the involvement of very early structures in visual-related changes following deafness.

One interesting aspect of the present finding is that response time advantages in deaf adults when responding to visual stimuli were not modulated by stimulus eccentricity. Indeed, the reaction time advantage of approximately 50 ms measured in deaf compared to hearing adults emerged regardless of visual stimulus eccentricity (see Fig. 1c). This is in line with other findings from the literature on speeded simple detection of visual targets (e.g. Bottari et al. 2010, 2011), and it provides further evidence in favour of the existence of some constraints to the notion that behavioural changes in people with profound deafness

should be maximal when visual stimuli occur at peripheral locations in the visual field (e.g. Bavelier et al. 2006).

The present findings also contribute to the emerging literature on somatosensory processing in early deaf adults. Until now, changes in the tactile domain following early auditory deprivation have been investigated without taking into consideration reaction times of participants (Bolognini et al. 2012; Frenzel et al. 2012; Heming and Brown 2005; Karns et al. 2012; Levänen and Hamdorf 2001; Moallem et al. 2010). The absence of tactile response time advantage in our deaf group is compatible with two interpretations. The first possibility is that only some aspects of tactile processing are potentiated in early deaf adults. For instance, tactile frequency discrimination could be selectively enhanced by profound deafness (Levänen and Hamdorf 2001), possibly as a consequence of reorganisation occurring within auditory regions (Levänen et al. 1998; Auer et al. 2007; Karns et al. 2012). By contrast, performance could remain unchanged—or even become impaired—following early deafness in other tasks such as grating orientation discrimination (Frenzel et al. 2012), vibration detection thresholds (Moallem et al. 2010; Frenzel et al. 2012), tactile temporal discrimination (Bolognini et al. 2012; Heming and Brown 2005; Karns et al. 2012; Moallem et al. 2010) and reaction times to tactile targets (the present study). A second possibility is that congenital deafness could be detrimental for proper developing of tactile processing. This account has recently been proposed by Frenzel et al. (2012), which documented a significant correlation between tactile and auditory acuity levels in the hearing population. In addition, they have also reported a significant impairment in vibrotactile sensitivity and tactile acuity in congenitally deaf participants and in patients with Usher syndrome with *USH2A* gene mutations compared to hearing controls. This led to the proposal that a common genetic determinant can affect both hearing and touch. This proposal, however, could be appropriate to explain deficits in tactile processing in profound deafness of genetic origins, whereas it might be less appropriate to account for other forms of deafness.

Recent reviews on the changes in brain and behaviour in conditions of sensory deprivation prompted a more systematic comparison between changes occurring in bilateral deafness and changes observed in complete blindness (e.g. Dormal and Collignon 2011; Merabet and Pascual-Leone 2010; Pavani and Röder 2012; Voss and Zatorre 2012). In this respect, it is interesting to note that also the literature on blindness has investigated changes in response time in the intact sensory modalities (typically audition and touch) in visually deprived individuals, thus providing a relevant parallel for the experiment described in the present study. However, different from the results reported for deaf adults, when blind individuals were tested in simple detection

tasks, reaction times to auditory and tactile stimuli were comparable to those of sighted controls (Collignon et al. 2006; Collignon and De Volder 2009). Instead, a reaction time advantage, irrespectively of the sensory modality tested, emerged for blind participants only for what Donders (1868/1969) defined as choice reaction times, namely reaction times in response to more complex tasks, which require some discrimination of specific stimuli features (Collignon et al. 2006; Collignon and De Volder 2009). We are not further discussing here the implications of these results as it is beyond the aim of the present study. However, it is relevant to highlight that the difference in behavioural changes exerted by blindness and deafness we have just introduced represents a good example of how deprivation in different sensory modalities (i.e. vision or audition) might result in different behavioural modifications (see Pavani and Röder 2012 for further discussion of this topic).

In conclusion, the present findings suggest that behavioural advantages triggered by auditory deprivation do not necessarily extend across *all* intact sensory modalities. This provides initial evidence that intact sensory modalities can reorganise independently from each other following early bilateral deafness. To the best of our knowledge, the only other study that tested the same behavioural ability in both vision and touch was conducted by Heming and Brown (2005). They revealed, however, a sensory-unspecific temporal order judgment deficit in deaf compared to hearing adults. Future research in the deaf population should compare visual and tactile performance in other abilities for which a visual enhancement has been documented (e.g. discrimination of moving stimuli directions; e.g. Bosworth and Dobkins 2002; Hauthal et al. 2013; Neville and Lawson 1987), to test whether they are selective to vision or extend also to touch.

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