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Research Paper

Spatial and non-spatial multisensory cueing in unilateral cochlear implant users

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A B S T R A C T

In the present study we examined the integrity of spatial and non-spatial multisensory cueing (MSC) mechanisms in unilateral CI users. We tested 17 unilateral CI users and 17 age-matched normal hearing (NH) controls in an elevation-discrimination task for visual targets delivered at peripheral locations. Visual targets were presented alone (visual-only condition) or together with abrupt sounds that matched or did not match the location of the visual targets (audio-visual conditions). All participants were also tested in simple pointing to free-field sounds task, to obtain a basic measure of their spatial hearing ability in the naturalistic environment in which the experiment was conducted. Hearing controls were tested both in binaural and monaural conditions. NH controls showed spatial MSC benefits (i.e., faster discrimination for visual targets that matched sound cues) both in the binaural and in the monaural hearing conditions. In addition, they showed non-spatial MSC benefits (i.e., faster discrimination responses in audio-visual conditions compared to visual-only conditions, regardless of sound cue location) in the monaural condition. Monaural CI users showed no spatial MSC benefits, but retained non-spatial MSC benefits comparable to that observed in NH controls tested monaurally. The absence of spatial MSC in CI users likely reflects the poor spatial hearing ability measured in these participants. These findings reveal the importance of studying the impact of CI re-afferentation beyond auditory processing alone, addressing in particular the fundamental mechanisms that serves orienting of multisensory attention in the environment.

1. Introduction

A cochlear implant (CI) is a neuroprostheses that affords partial recovery of auditory sensations and speech understanding in people suffering severe to profound hearing loss (Moore and Shannon, 2009; Wilson and Dorman, 2008). Although CI surgery is indicated for people with *bilateral* hearing loss, most patients receive only one CI, and therefore experience unilateral hearing. The restricted spectro-temporal processing provided by the CI processor (Majdak et al., 2011) combined with the absence or reduction of binaural input (i.e., bimodal CI users individuals who continue to use a hearing aid in the ear contralateral to the implant) limit efficient spatial hearing. Sound localisation is typically at or near chance in unilateral CI users (Buhagiar et al., 2004; Grantham et al., 2008; Luntz et al., 2005; Nava et al., 2009a; Noble et al., 2009; Tyler et al., 2009), with better localisation abilities reported in some of the bimodal users (Potts et al., 2009; Seeber et al., 2004). The consequences of auditory spatial deficits in unilateral CI users have been primarily examined in relation to speech understanding (e.g., Tyler et al., 2009; van Hoesel and Tyler, 2003; for review see Ching et al., 2007). More recent evidence also indicates higher listening effort in unilateral compared to bilateral CI users (Hughes and Galvin, 2013). Instead, to the best of our knowledge, it has never been explored how sound-localisation abilities in CI users affects allocation of spatial visual attention and how this impacts the

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selection of relevant information from the multisensory environment. Likewise, non-spatial auditory influences on visual processing (e.g., Andersen and Mamassian, 2008; Ngo and Spence, 2010; Noesselt et al., 2008; Van der Burg et al., 2008) also remained largely overlooked (but see Harris and Kamke, 2014; Kamke et al., 2014). The present study aimed to investigate the consequences of unilateral CI on visual and audio-visual attention, building on two decades of studies on multisensory links in attention-orienting (for reviews see Hillyard et al., 2015; Spence, 2010).

A first important example of multisensory links concerns the deployment of spatial visual attention in the context of abrupt auditory events. There is no question that sudden sounds can capture attention, that is, they can result in a transient allocation of visual resources towards their location (Spence, 2010). This type of automatic and exogenous cue in multisensory attention has been documented with all combinations of sensory stimuli and results in behavioural benefits that are adaptive in the interactions with the environment (Spence and Driver, 1997; Störmer et al., 2009). One key determinant of this exogenous multisensory interaction is the spatial proximity between the successive multisensory stimulations (Spence, 2010). Although multisensory links in exogenous attention have been demonstrated also when successive stimuli are delivered from different locations within the same spatial hemifield (e.g., Frassinetti et al., 2002; Schmitt et al., 2010), the interactions and potential benefits are strongest when the successive stimuli originate from the same spatial location (Prime et al., 2008).

To the authors knowledge, the interactions between abrupt sound stimuli and orienting of visual attention have not been investigated in cochlear implant users. Given the key role of spatial proximity in exogenous multisensory cueing, it can be hypothesised that the reduced auditory spatial abilities of unilateral CI users should heavily impact on the integrity of this multisensory orienting mechanism. While this seems trivial it remains an empirical question. Evidence suggests that increased uncertainty regarding the spatial location of sounds (i.e., measured in a separate task that requires identification of the sound source in space) does not necessarily imply the immediate elimination of audio-visual spatial cueing effects. An example of this dissociation has been documented in the neuropsychological literature that examined auditory space perception and audio-visual cueing in brain-damaged patients with hemispatial neglect. Neglect patients show increased uncertainty when localising sounds in contralesional compared to ipsilesional space (Pavani et al., 2001), and show rightward biases when pointing to sounds (for review see Pavani et al., 2004). Nonetheless, they benefit from spatial correspondences between auditory and visual stimuli when detecting visual targets in contralesional space (Frassinetti et al., 2002). The first aim of the present study was to examine spatial multisensory cueing in unilateral CI users to test whether sudden sounds influence visual spatial attention in a similar manner to hearing controls.

A second example of multisensory links concerns a non-spatial multisensory enhancement that may occur independently of spatial multisensory cueing. The mere presence of a sound just prior to the presentation of the visual target might benefit performance, that is regardless of whether the location of the sound matches that of the visual target (e.g., Andersen and Mamassian, 2008; Ngo and C. Spence, 2010; Noesselt et al., 2008; Van der Burg et al., 2008). This effect is not just the consequence of sounds alerting participants and modulating response preparation, as documented by the fact that these multisensory advantages promoted visual discrimination (Noesselt et al., 2008) or reduced masking (Ngo and Spence, 2010; Van der Burg et al., 2008). Thus a second aim of this work was to investigate non-spatial multisensory cuing in unilateral CI users. Though the ability to localise sounds in space is likely significantly reduced in CI users, multisensory integration might not be completely lost. Specifically, the ability to generally detect the presence sounds might still affect subsequent responses to visual targets, restoring the integrity of this multisensory advantage in CI users. Looking at both a spatial and non-spatial multisensory effects in CI users might help to provide further insight in the relative interdependence of sound detection and localisation.

A third example of multisensory links in spatial attention can be found in the context of sustained attentional biases where the expectation of events occurring in one modality has been found to affect the detections of events in another modality. That is, when observers attend towards one hemispace to monitor one modality (e.g., audition), allocation of resources in a different modality (e.g., vision) is typically also biased towards the same region of space. For instance, in a now classic audio-visual experiment conducted by Spence and Driver (Spence and Driver, 1996; Experiment 4), participants were asked to discriminate the elevation of auditory and visual targets, delivered in the left or right hemispace. At the beginning of each block, participants were informed that auditory targets were more likely on one side of space compared to the other one. Instead, visual targets were overall less frequent and were in fact delivered with a higher proportion on the unattended than the attended auditory side. As expected, the results showed that participants were faster and more accurate at discriminating the elevation of auditory targets on the attended side. However, of critical importance here was that this attentional facilitation extended to visual targets that appeared on the attended *auditory* side, even though these visual targets were more likely to occur on the unattended auditory side. This link between sustained allocation of resources for one modality and attention biases for another modality has now been documented behaviourally for multiple multisensory combinations (Lloyd et al., 2003; Spence et al., 2000).

As third aim, we explored whether the unilateral hearing experience of unilateral CI users may result in sustained orienting of auditory attention towards the implant side which could consequently bias visual attention. Specifically, evidence suggests that sound localisation biases exist in situations of monaural hearing. Hearing individuals with a temporary monaural ear-plug show systematic misperceptions of sounds towards the hemispace ipsilateral to the open ear (Butler et al., 1990; Oldfield and Parker, 1986; Slattery and Middlebrooks, 1994). Likewise, patients with single sided deafness (SSD) can show sound localisation biases towards the side of space ipsilateral to the hearing ear (Slattery and Middlebrooks, 1994; Van Wanrooij and Van Opstal, 2004). Finally, there is evidence suggesting that unilateral CI users are more likely to localise sounds towards the implant side (Nava et al., 2009a). If monaural hearing results in sustained and systematic auditory biases in unilateral CI users, attention biases towards the implant side may also extend to the visual modality.

To experimentally address these aims we tested a group of unilateral CI participants in a series of auditory, visual and audio-visual tasks. First, we measured sound localisation ability for each participant, asking patients to point to free-field sounds delivered from four hidden loudspeakers in front space. This basic sound-localisation task served to measure the degree of spatial uncertainty when perceiving sounds in the experimental environment, as well as detect any systematic bias towards the implant side. Second, we tested participants in an elevation-discrimination task, in which peripheral visual targets were presented together with abrupt sounds that matched or not-matched the spatial position of the visual targets. This audio-visual task examined whether sounds in specific locations spatially cue visual attention in monaural CI users, as it is typically found in hearing individuals. Finally, the elevation-discrimination task was also conducted as a visual-only