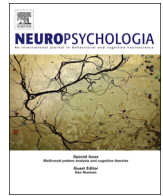




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Crossmodal enhancement of visual orientation discrimination by looming sounds requires functional activation of primary visual areas: A case study



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ABSTRACT

Approaching or looming sounds are salient, potentially threatening stimuli with particular impact on visual processing. The early crossmodal effects by looming sounds (Romei, Murray, Cappe, & Thut, 2009) and their selective impact on visual orientation discrimination (Leo, Romei, Freeman, Ladavas, & Driver, 2011) suggest that these multisensory interactions may take place already within low-level visual cortices. To investigate this hypothesis, we tested a patient (SDV) with bilateral occipital lesion and spared residual portions of V1/V2. Accordingly, SDV's visual perimetry revealed blindness of the central visual field with some residual peripheral vision. In two experiments we tested for the influence of looming vs. receding and stationary sounds on SDV's line orientation discrimination (*orientation discrimination* experiment) and visual detection abilities (*detection* experiment) in the preserved or blind portions of the visual field, corresponding to spared and lesioned areas of V1, respectively. In the visual *orientation discrimination* experiment we found that SDV visual orientation sensitivity significantly improved for visual targets paired with looming sounds but only for lines presented in the partially preserved visual field. In the visual *detection* experiment, where SDV was required to simply detect the same stimuli presented in the *orientation discrimination* experiment, a generalised sound-induced visual improvement both in the intact and in blind portion of the visual field was observed. These results provide direct evidence that early visual areas are critically involved in crossmodal modulation of visual orientation sensitivity by looming sounds. Thus, a lesion in V1 prevents the enhancement of visual orientation sensitivity. In contrast, the same lesion does not prevent the visual detection enhancement by a sound, probably due to alternative visual pathways (e.g. retino-colliculo-extrastriate) which are usually spared in these patients and able to mediate the crossmodal enhancement of basic visual abilities such as detection.

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1. Introduction

From an evolutionary perspective, multisensory integration represents a successfully adaptive mechanism, whereby information from several sensory modalities is integrated to produce a coherent, unified sensory percept (Stein & Meredith, 1993; Stein, Meredith, & Wallace, 1993). Multisensory integration results in perceptual gain in many circumstances, for example by reducing perceptual ambiguity (MacLeod & Summerfield, 1990), enhancing

stimulus detection (Bolognini, Frassinetti, Serino, & Ladavas, 2005; Frassinetti, Pavani, & Ladavas, 2002) or speeding up responses (Miller, 1982; Molholm et al., 2002; Schroger & Widmann, 1998).

Vision is a paramount sense in humans and it has been long considered a self-contained modality, which prevails over other sensory modalities and unidirectionally influences them, as shown in healthy subjects (Bertini, Leo, Avenanti, & Ladavas, 2010; Bolognini, Leo, Passamonti, Stein, & Ladavas, 2007; for reviews, see Ernst & Bulthoff, 2004; Shams & Kim, 2010) and in patients (for a review, see Làdavas, 2008; Leo, Bolognini, Passamonti, Stein, & Ladavas, 2008; Passamonti, Frissen, & Ladavas, 2009). However, recent accounts have challenged the visual dominance hypothesis, showing that also audition can influence vision, for example enhancing it when degraded (Frassinetti, Bolognini, Bottari,

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Bonora, & Ladavas, 2005; Passamonti, Bertini, & Ladavas, 2009) or even biasing it, thus generating sound-induced visual illusions (for a review, see Shams & Kim, 2010). Accordingly, studies on healthy subjects have shown that the presentation of sounds can enhance visual detection (de Haas, Cecere, Cullen, Driver, & Romei, 2013; Driver & Spence, 1998; McDonald, Teder-Salejarvi, & Hillyard, 2000; Vroomen & de Gelder, 2000), phosphene (i.e. illusory visual percepts induced by transcranial magnetic stimulation), perception (Bolognini, Senna, Maravita, Pascual-Leone, & Merabet, 2010; Romei et al., 2009) and visual orientation sensitivity (Leo, Romei, Freeman, Ladavas, & Driver, 2011). More germane to the present study, auditory stimulation has been proven to enhance visual detection also in patients with visual field defects due to lesions to the geniculostriate pathway (Bolognini, Rasi, Coccia, & Ladavas, 2005; Frassinetti et al., 2005; for a review, see Ladavas, 2008). In particular, Frassinetti et al. (2005) reported that hemianopic patients who could not detect brief spots of light when presented alone in their blind field, improved their visual detection sensitivity when visual stimuli were coupled with spatio-temporally coincident, but not spatially disparate, sound bursts, suggesting a role of colliculo-extrastriate visual pathways bypassing V1 in mediating such a type of crossmodal visual enhancement.

Notably, auditory stimuli with different characteristics can crossmodally modulate vision in different ways. Sounds signalling approach (looming sounds) have been shown to induce perceptual bias compared to other types of sounds, both in monkeys (Ghazanfar, Neuhoff, & Logothetis, 2002; Maier & Ghazanfar, 2007) and humans (Hall & Moore, 2003; Neuhoff, 1998; Seifritz et al., 2002). For example, human listeners tend to overestimate looming sound intensity relative to intensity-matched receding sounds (Neuhoff, 1998) as well as to underestimate the temporal point of contact of looming sound sources (Rosenblum, Carello, & Pastore, 1987). Moreover, looming sounds seem particularly efficient in modulating visual processing in animals (Maier, Chandrasekaran, & Ghazanfar, 2008; Maier, Neuhoff, Logothetis, & Ghazanfar, 2004) as well as in humans (Leo et al., 2011; Romei et al., 2009; Schouten, Troje, Vroomen, & Verfaillie, 2011). A psychophysical study on healthy subjects by Leo et al. (2011) reported that spatio-temporally congruent looming sounds, compared to receding and stationary sounds, improved orientation sensitivity (d') for Gabor patches presented at the individual orientation discrimination threshold and in peripheral view. However, despite the notion that visual orientation discrimination is considered a primary function of early visual areas (Hubel & Weisel, 1959; Hubel & Wiesel, 1977), the paradigm used by Leo et al. (2011) could not directly identify whether the visual orientation discrimination enhancement by looming sounds was mediated by subcortical multisensory structures (e.g., the superior colliculus; Stein & Meredith, 1993) or by other areas with multisensory properties such as higher associative cortices or the primary visual cortex. Indeed, converging evidence suggests that multisensory interactions might not only occur in subcortical structures (Hackett, 2012; Nagy, Eordeghe, Paroczky, Markus, & Benedek, 2006; Nishijo, Ono, & Nishino, 1988; Stein & Meredith, 1993) and higher associative cortices (e.g., superior temporal and intraparietal sulci; Ghazanfar & Schroeder, 2006; Kayser & Logothetis, 2007), but also at the level of early (primary) sensory areas (Cappe, Thelen, Romei, Thut, & Murray, 2012; Giard & Peronnet, 1999; Kayser, Petkov, Augath, & Logothetis, 2007; Martuzzi et al. 2007; Molholm et al., 2002; Murray, Cappe, Romei, Martuzzi, & Thut, 2012; Noesselt et al. 2010; Rajj et al., 2010; Romei, Murray, Merabet, & Thut, 2007; Van der Burg, Talsma, Olivers, Hickey, & Theeuwes, 2011; Wang, Celebrini, Trotter, & Barone, 2008).

The present study used a lesion approach to directly test the hypothesis that early visual areas are crucially involved in visual

orientation sensitivity enhancement induced by looming sounds. To this end, we tested SDV, a patient with partial bilateral occipital lesion, presenting him with audio-visual stimuli either in the relatively preserved or in the blind portion of his visual field in two separate experiments.

In the visual *orientation discrimination* experiment, akin to Leo et al. (2011) we used sounds (looming, receding and stationary) in combination with a psychophysical measure of visual orientation discrimination for solid white lines presented either in vertical or tilted position (anti-clockwise from vertical). The patient had to judge on each trial whether the visual stimulus was vertically oriented or tilted. We manipulated whether visual stimuli were presented in the relatively intact or in the blind visual field, while looming, receding or static sounds were presented in spatio-temporal coincidence with visual targets. Based on previous findings that looming sounds selectively enhance orientation sensitivity (Leo et al., 2011) and early visual cortex excitability (Romei et al., 2009), we predicted enhanced visual orientation discrimination sensitivity (d') by looming sounds but not other types of sound. Crucially, if early visual cortex plays a causative role in the orientation discrimination enhancement by looming sounds, such a crossmodal effect should occur only for visual stimuli presented in the relatively preserved portion of the visual field, which is subtended by spared visual cortex. In contrast, no enhancement should be observed when stimuli are presented in the blind portion of the visual field.

In addition, we tested SDV in a visual *detection* experiment requiring to simply detect the same visual stimuli presented in the *orientation discrimination* experiment. In this experiment sounds were presented either in the same position as the visual targets or in different position. In line with previous studies suggesting that the crossmodal enhancement of visual detection depends on colliculo-extrastriate projections bypassing V1 (Frassinetti et al., 2005; Ladavas, 2008) and in accordance with the spatial rule of multisensory integration (Stein & Meredith, 1993; Stein et al., 1993), we expected crossmodal visual detection enhancement by spatially coincident sounds when visual stimuli were presented both in SDV's relatively preserved and in his blind visual field, i.e. also in the absence of functional visual cortex.

2. Case history

SDV is a 44 year old man who had a cardiac arrest due to electrocution, with consequent cerebral anoxia affecting bilateral occipital cortex, 3 years before participating in the present study. Neuroradiological MRI examination revealed two encephalomalacic areas involving the grey and white matter of both the occipital lobes, corresponding to the BA 17–18, and to the BA 19 partially. The lesion extended rostrally to the superior parietal lobes, corresponding to the BA 30–31 and partially to the BA 7 (see Fig. 1). Following the event SDV suffered cortical blindness for almost 10 months, then he partially recovered vision especially in the periphery of the visual field. A campimetry test (Medmont M700 automated perimetry, Melbourne, Australia) performed before the experimental testing showed a complete loss of central vision (covering an area of five visual degrees radius), plus the presence of multiple scotomas, predominantly in the lower visual field (see Fig. 2).

Despite his visual field defect, SDV was able to perceive movement and colours, navigate and interact with the environment and he could independently carry out basic everyday life activities (feeding, dressing, etc.). However, since the incident, the patient's ability to identify objects and people by sight was compromised (visual agnosia).

For a detailed description of SDV's clinical and lesional profile, refer to Serino et al. (2014).

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