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Listening to numbers affects visual and haptic bisection in healthy individuals and neglect patients

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ABSTRACT

There is evidence that humans represent numbers in the form of a mental number line (MNL). Here we show that the MNL modulates the representation of visual and haptic space both in healthy individuals and right-brain-damaged patients, both with and without left unilateral spatial neglect (USN). Participants were asked to estimate the midpoint of visually or haptically explored rods while listening to task-irrelevant stimuli: a small digit ("2"), a large digit ("8"), or a non-numerical auditory stimulus ("blah"). In a control silent condition, the bisection error of USN patients was biased rightwards (namely, the marker of USN) only in the visual modality. Regardless of the direction of the bisection error committed in silent trials, listening to the small digit shifted the perceived midline leftwards, and listening to the large digit shifted the perceived midline rightwards, compared to a control condition in which a neutral syllable ("blah") was presented. The shift induced by listening to numbers occurred independently of the modality of response (i.e., both in vision and haptics), and in every group of participants. Interestingly, the effect of auditory numbers processing on space estimation was overall larger for haptically than for visually explored space in all participants. In conclusion, the present data show that listening to irrelevant numbers affects space perception also in patients with left USN, indicating that the spatial representation and attention processes disrupted by USN are not involved in these numerical magnitude-spatial effects.

1. Introduction

Numbers are typically represented in a spatial format that takes the form of a mental number line (MNL; see Dehaene, Bossini, & Giraux, 1993), that – in left-to-right reading cultures – appears to be left-to-right oriented. Accordingly, small numbers occupy the left side of the MNL, and large numbers the right side. There is evidence for similar biases in the way attention is allocated to physical space, and to the space of the MNL. In particular, neurologically unimpaired individuals tend to show a leftward directional bias – often referred to as "pseudoneglect" (for a review, see Jewell & McCourt, 2000) – both when bisecting physical lines and numerical intervals (Cattaneo, Fantino, Tinti, Silvanto, & Vecchi, 2010; Longo & Lourenco, 2007), although the mechanisms underlying pseudoneglect for numerical and physical lines bisection may not overlap completely (e.g., Ashkenazi & Henik, 2010).

Importantly, the spatial representation of numbers and the perception of physical space affect each other (see Umiltà, Priftis, & Zorzi, 2009; Wood, Willmes, Nuerk, & Fischer, 2008, for reviews). For instance, visually presented small numbers bias attention toward the left side of physical space, and visually presented large numbers bias attention to the right side of it (Fischer, Castel, Dodd, & Pratt, 2003). Correspondingly, activating the representation of specific portions of space affects numerical processing (Cattaneo, Fantino, Silvanto, Vallar, & Vecchi, 2011; Stoianov, Kramer, Umiltà, & Zorzi, 2008). Such interaction can also occur across sensory modalities: in particular, listening to small and large magnitude numbers while haptically estimating the length of a rod shifts its perceived midline respectively to the left and to the right of the true midpoint in neurologically unimpaired participants (Cattaneo et al., 2010).

Critically, whether space perception is affected by processing numerical magnitudes to a similar extent in different sensory modalities is not known so far. A recent study demonstrates that auditorily presented numbers affect length estimation of haptically

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perceived rods (Cattaneo et al., 2010), but whether this effect is also present and – if so – to a similar extent when the length of visually presented rods has to be judged has not been investigated yet. In fact, it could prove to be the case that the visual modality is more "resistant" against the attentional biases induced by the concurrent auditory presentation of numbers, being vision usually the most precise modality for judging spatial location and spatial extent (with the modality that "dominates" in a specific situation being the one that is more precise for the task being performed, see Ernst & Banks, 2002; Welch & Warren, 1986).

Moreover, it has not been previously investigated whether auditorily presented numbers can affect the representation of space in patients affected by unilateral spatial neglect (USN). This is a deficit, typically brought about by right hemispheric lesions, whereby patients are not able to report stimuli presented in the portion of space contralateral to the side of the lesions (namely, the left-hand-side in right-brain-damaged patients), and to explore that side of space (Halligan, Fink, Marshall, & Vallar, 2003; Heilman, Watson, & Valenstein, 2003; Husain, 2008; Vallar, 1998, 2001). One task frequently used to assess USN – both for diagnostic and research purposes – is "line bisection", where participants are required to mark the perceived mid-point of a line that, in order to assess lateral USN, is presented horizontally. Right-brain-damaged patients with left USN typically bisect the line to the right of the veridical midpoint, therefore underestimating its left portion (Bisiach, Bulgarelli, Sterzi, & Vallar, 1983; Bisiach, Capitani, Colombo, & Spinnler, 1976; Schenkenberg, Bradford, & Ajax, 1980; Vallar, Daini, & Antonucci, 2000). Notably, also the horizontal spatial representation of numbers is distorted in USN patients (despite a spared abstract knowledge of numerical quantities, see Pia, Corazzini, Folegatti, Gindri, & Cauda, 2009; Vuilleumier, Ortigue, & Brugger, 2004). In particular, right-brain-damaged patients with left USN may show a rightward bias in setting the mid-point of auditorily presented numerical intervals (Zamarian, Egger, & Delazer, 2007; Zorzi, Priftis, & Umiltà, 2002), and a representational neglect of the left portion of the MNL in other paradigms such as judging whether a given number represents the midpoint of a numerical interval (Hoeckner et al., 2008), or comparing numerical magnitudes (Vuilleumier et al., 2004). Interestingly, in a left-brain-damaged patient with right USN, an opposite pattern has been described (Pia et al., 2009).

Other interactions between spatial and numerical representations, however, appear not to be prevented by USN: in particular, numbers presented visually at the extremities of a to-be-bisected visual line affect the bisection performance of right-brain-damaged patients with left USN (Bonato, Priftis, Marenzi, & Zorzi, 2008). Specifically, the bisection error is displaced leftward (i.e., contralaterally with respect to the side of the lesion) when a small digit is presented, and rightward (i.e., ipsilaterally to the side of the lesion) when a large digit is presented (for reviews on the relationship between spatial and numerical representations see de Hevia, Vallar, & Girelli, 2008; Umiltà et al., 2009). So far, no studies have ever investigated whether listening to task-irrelevant numbers affects spatial judgments in the visual and haptic modality in right-brain-damaged patients with USN, as assessed by line bisection. In this study, a group of neurologically unimpaired participants and a group of patients with right hemisphere lesions, with and without evidence of left USN, were required to bisect rods of different length in the visual and haptic modalities, while concurrently listening to numerical cues of a different magnitude. Were the attentional modulation induced by numbers processing the same across sensory modalities, putative shifts in the bisection bias should be comparable in the visual and in the haptic tasks. Moreover, finding evidence for an effective modulation by auditorily presented numbers on bisection performance in right-brain-damaged patients with left USN shall contribute to shed light on the nature of the attentional deficits induced by USN, and on the neural circuits mediating numbers-space interactions in neurologically unimpaired individuals.

2. Methods

2.1. Participants

Nineteen patients with right hemisphere brain lesions, confirmed by CT or MRI scan, participated in the study and were recruited from the inpatient population of the Neurorehabilitation Unit of the IRCCS Italian Auxological Institute, Milan, and of the Neuropsychological Unit, Ospedali Civili di Brescia, Brescia, Italy. Patients gave written informed consent to the study, that was approved by the Ethical Committee of the IRCCS Italian Auxological Institute, Milan, Italy. The patients' demographic and neurological features are summarized in Table 1. All patients were right-handed, according to a standard interview (Oldfield, 1971), and had no history or evidence of previous neurological or psychiatric diseases. All patients had a normal or corrected-to-normal vision. Nine patients (N+ group) had left USN (4 males, mean age = 67.4, SD ± 10.4, mean years of education = 9.4), whereas 10 patients (6 males, mean age = 49.2, SD ± 9.2, mean years of education = 12.6) showed no USN (N− group). The presence of USN was assessed by a battery of standard tests (see Table 2): patients were assigned to the N+ group if they showed a rightward bias in line bisection, and evidence of left USN in at least one of the cancellation tests, and in one of the other screening tests (see below). Contralesional motor, somatosensory, and visual half-field deficits, including extinction to tactile and visual stimuli, were assessed by a standard neurological exam (Bisiach, Cappa, & Vallar, 1983). None of the patients showed a cognitive deficit, as evaluated by the Mini Mental State Evaluation (Grigoletto, Zappala, Anderson, & Lebowitz, 1999). Control data were provided by two groups of right-handed neurologically unimpaired participants, matched for gender, age, and education with the N+ and the N− groups. The C+ group (control for the N+ patients) consisted in 9 participants (4 males, mean age = 66.1, SD ± 10.6, mean years of education = 10.9), the C− (control for the N− patients) group consisted in 10 participants (6 males, mean age = 49.6, SD ± 9.2, mean years of education = 13.2). Each participant gave informed written consent to take part in the experiment. All participants were treated in accordance with the Declaration of Helsinki.

Lesions were mapped for each right-brain-damaged patient using the MRIcro software (Rorden & Brett, 2000) and were drawn manually onto selected horizontal slices of a standard template brain. MNI z-coordinates of each transverse section are given. Fig. 1 shows the overlapped lesion maps of 18 of the 19 right-brain-damaged patients, subdivided into showing and not showing left USN, and the colour-coded relative frequency of damage in the N+ group after subtraction of the N− group. In N+ patients the maximum overlap involved the right putamen and the insula (8 patients); in N− patients a puntiform maximum overlap was observed over the posterior part of the right putamen (4 patients). The subtraction identified a region localised in the right insula and putamen as associated to the USN deficits. Overall, lesions were more extensive in the N+ group (mean volume of the lesion = 87.16 cc, SD ± 81.88) than in the N− group (mean volume of the lesion = 35.04 cc, SD ± 43.72), a result that is in line with previous evidence (e.g., Hier, Mondlock, & Caplan, 1983a,b; Leibovitch et al., 1998). Scan images were unavailable for N− patient #3; medical records for this patient reported ischemic lesions in the internal capsule, the thalamus and the cerebellum.

2.2. Baseline neuropsychological assessment

The diagnostic battery assessing the presence of left unilateral neglect included: three visuomotor exploratory tasks [line (Albert, 1973), letter and bell cancellation (for the cut-off criteria of these two tests we referred to the normative data reported in Vallar, Rusconi, Fontana, & Musicco, 1994)], sentence reading (Pizzamiglio et al., 1992), line bisection (for the cut-off criteria of this test we referred to Fortis et al., 2010), and three drawing tasks (daisy copying, clock from memory and the five-element complex drawing copying test, Gainotti, Messerli, & Tissot, 1972; for cut-off criteria we referred to Fortis et al., 2010, and to normative unpublished data by Corbetta, 2008). Patients used their right unaffected hand to perform each cancellation, bisection, and drawing task. In each task, the centre of the sheet was aligned with the mid-sagittal plane of the trunk of the patients, who were free to move their head and eyes.

2.2.1. Line bisection

The patients' task was to mark with a pencil the midpoint of six horizontal black lines (two 10 cm, two 15 cm, and two 25 cm in length, all 2 mm in width), presented in a random-fixed order. Each line was printed in the centre of an A4 sheet, aligned with the mid-sagittal plane of the participant's body. The length of the left-hand side of the line (i.e., from the left end of the line to the participant's mark) was measured to the nearest mm. This measure was converted into a standardized score (percent deviation), namely: measured left half minus objective half/objective half × 100 (cf. Rode, Michel, Rossetti, Boisson, & Vallar, 2006). This transformation yields positive numbers for marks placed to the right of the physical centre, negative numbers for marks placed to the left of it (line bisection error: LBE). According to normative