Neuropsychologia 51 (2013) 1925–1932

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

Spatial bias in symbolic and non-symbolic numerical comparison in neglect

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ARTICLE INFO

Article history:
Received 7 January 2013
Received in revised form
22 May 2013
Accepted 5 June 2013
Available online 15 June 2013

Keywords:
Spatial neglect
Numbers
Symbolic and non-symbolic inputs

ABSTRACT

When asked to bisect mentally numerical intervals, neglect patients show a displacement of the numerical midpoint similar to the one observed in physical line bisection. This spatial-numerical bias has been taken as evidence of the spatial nature of numerical magnitude representations. However, to date, neuropsychological studies in neglect patients have only used symbolic numerical material. Here, we compare the results of patients with right-hemisphere damage with and without unilateral left neglect and age-matched healthy control participants in two numerical comparison tasks using symbolic and non-symbolic materials, in order to determine whether the representation of non-symbolic numerosities was altered or not by the presence of neglect. When asked to judge if an Arabic digit or a sequence of flashed dots was smaller or larger than a reference value (i.e., 5), the responses of neglect patients to smaller magnitudes (i.e., 4) were impaired. Moreover, only neglect patients presented an asymmetrical distance effect (i.e., an enhanced effect only for stimuli of smaller numerical magnitude than the reference). These results provide the first direct evidence of a spatial bias in non-symbolic numerosity in neglect patients, and support the existence of common processing mechanisms and/or a representational system for symbolic and non-symbolic inputs.

1. Introduction

Interactions between number and space processing have been reported in many studies (for a review, see Hubbard, Piazza, Pinel, & Dehaene, 2005), which has led to the suggestion that numerical magnitudes may be represented spatially with small numbers on the left and large numbers on the right side of a mental number line (Dehaene, 1992). To test the spatial nature of this numerical representation, recent neuropsychological research has investigated numerical abilities in neglect patients. Unilateral spatial neglect is defined as a failure to report, respond to or orient towards stimuli in contra-lesional space (Heilman, 1979) that often occurs after cerebral lesions involving the posterior-inferior parietal and the premotor cortices (Vallar, 1998), and that could possibly arise from a disruption of fronto-parietal white matter pathways (Doricchi & Tomaiuolo, 2003; Doricchi, Thiebaut de Schotten, Tomaiuolo, & Bartoloméo, 2008). When asked to indicate the midpoint of a physical line, neglect patients show a significant rightward deviation (e.g., Binder, Marshall, Lazar, Benjamin, & Morh, 1992; Marshall & Halligan, 1989; Pizzamiglio, Committeri, Galati, & Patria, 2000). Neglect is not restricted to the perception of physical space and may extend to representational space. Indeed, there is evidence that neglect patients fail to recall the left side of well-known places, depending on their imagined viewpoint (e.g., Bisiach & Luzzatti, 1978). Nevertheless, a double dissociation between perceptual and representational neglect has been observed, suggesting the existence of at least partly independent attentional mechanisms operating in the perceptual and imaginal space (Anderson, 1993; Guariglia, Padovani, Pantano, & Pizzamiglio, 1993).

In numerical interval bisection tasks (i.e., determining the midpoint of a numerical interval), left neglect patients showed a displacement of the midpoint towards large numbers, suggesting a deviation to the right part of the mental number line (Cappelletti, Freeman, & Cipolotti, 2007; Hoeckner et al., 2008; Zorzi, Priftis, & Umiltà, 2002; Zorzi, Priftis, Meneghello, Marenzi, & Umiltà, 2006). A case study of a right unilateral neglect patient showing the opposite bias (i.e., underestimation rather than overestimation of the midpoint; Pia, Corazzini, Folegatti, Gindri, & Cauda, 2009) supports the idea of a distortion of numerical representation caused by a deviation of visuospatial attention (however, see below van Dijck, Gevers, Lafosse, Doricchi, & Fias, 2011 for a rightward bias in a right neglect patient). Moreover, it has recently been demonstrated that neglect patients who present prismatic adaptation as a consequence of having worn shifting prisms (Rossetti et al., 2004) or who have received leftward optokinetic stimulation[1] (Priftis, Pitteri, Meneghello, Umiltà, & Zorzi, 2012), both techniques inducing visuo-spatial shifts of attention to the left, showed a reduction in the

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[1] Optokinetic stimulation is a technique inducing visuospatial shifts of attention by means of activation of the optokinetic nystagmus (for a review, see Kerkhoff, 2003).

0028-3932/$ - see front matter
http://dx.doi.org/10.1016/j.neuropsychologia.2013.06.004

overestimation bias. When neglect patients had to judge a given number as smaller or larger than a fixed reference number, they processed numbers just smaller than the reference more slowly than those just larger (Vuilleumier, Ortigue, & Brugger, 2004): when asked to compare numbers to a standard reference of 5, the patients were slower to respond to 4 than to 6, while they were slower to respond to 6 than to 8 when the reference was 7. This asymmetrical distance effect implies that neglect does not alter the representation of numbers per se, but induces a failure to access the left side of the mental number line relative to the standard. Random dot kinetograms (RDK, a technique that induces a perception of movement without eye movements) to the left also reduced this spatial bias in symbolic comparison tasks (Salillas, Granà, Juncadella, Rico, & Semenza, 2009). Taken together, these findings suggest that numerical judgements are biased by impaired spatial processing, which provides strong evidence of a numerical representation with spatial properties.

However, the double dissociation between physical line and numerical interval bisection impairments found in some neglect and non-neglect patients (Aiello, Merola, & Doricchi, 2013; Aiello et al., 2012; Doricchi, Guarglia, Gasparini, & Tomaiuolo, 2005; for a review, see Rossetti et al., 2011) questions the idea of a simple functional equivalence between the mental number line and the representation of physical space. Indeed, not all neglect patients show a numerical impairment and, conversely, some right brain-lesioned non-neglect patients show a spatial-numerical bias during mental bisection of number intervals. In the sample tested by Doricchi et al. (2005), only patients with lesions in the prefrontal cortex, a region known to support some working memory processes, showed a rightward numerical bias, suggesting that this region contributes to activating a numerical continuum in visuospatial working memory. An additional argument in favour of a working memory account comes from a case study of a patient with an extended left hemispheric lesion who presented spatial neglect for the right visual hemispace but left neglect for numbers (i.e., overestimation of the midpoint of number interval bisection; van Dijck et al., 2011). This patient had difficulty retrieving the first items of verbal sequences, suggesting that the overestimation in number interval bisection observed in neglect patients could originate in verbal working memory impairment for the initial items. Moreover, the role of working memory in spatial-numerical associations has been supported by several behavioural studies showing that the ordinal information stored in verbal working memory can overcome the spatial-numerical interaction based on magnitude (Fias, van Dijck, & Gevers, 2011; van Dijck & Fias, 2011).

The actual meaning of the spatial-numerical bias observed in neglect patients is thus unclear, as it could be due either to the spatial properties of a long-term representation or to order-related processes in short-term working memory. In this context, using non-symbolic stimuli may provide a significant way of disentangling these two possibilities. On the one hand, computational modelling suggests that symbolic and non-symbolic numerical inputs are coded by specific mechanisms, but are represented within a common numerical magnitude system (Verguts & Fias, 2004), possibly implemented in the left and right parietal cortices (Dormal, Andres, Dormal, & Pesenti, 2010; Holloway, Price, & Ansari, 2010; Piazza, Pinel, Le Bihan, & Dehaene, 2007; Santens, Roggeman, Fias, & Verguts, 2010; Venkatraman, Ansari, & Chee, 2005). Furthermore, various magnitudes (e.g., numerosity, length, duration, etc.) may be represented, irrespective of their mode of presentation, within a common magnitude processing system, possibly located in the parietal cortex (Bonato, Zorzi, & Umiltà, 2012; Walsh, 2003). Accordingly, the spatial-numerical bias should occur when processing symbolic but also non-symbolic stimuli. Yet, despite a growing interest in the neuropsychological investigation of unilateral neglect in the numerical domain, the studies so far have only tested spatial-numerical biases with symbolic notations. To the best of our knowledge, only one study to date has attempted to demonstrate the existence of a spatial bias in the perception of non-symbolic numerosities in healthy participants (de Hevia & Spelke, 2009). In a line bisection task flanked with a 2-dot and a 9-dot array, a shift of the subjective midpoint of the line in the direction of the numerically larger set of dots was observed. However, this experiment has been criticised because some non-numerical parameters were not controlled (e.g., area; Gebuis & Gevers, 2011). The assumption that processing non-symbolic magnitudes involves spatial representations is thus still an open question. On the other hand, non-symbolic sequential comparison requires more working memory resources than symbolic comparison, as the traces of each single presented dot must be somehow kept active to compare the target sequence to the standard. Therefore, patients with lower verbal working memory capacities should perform globally worse in this demanding task than controls with preserved working memory abilities. Finally, according to a working memory account, a bias for processing numerical magnitudes smaller than a reference in neglect patients should occur concomitantly with verbal working memory impairment (Doricchi et al., 2005).

The present study thus aims to determine whether or not the spatial bias observed in neglect patients when comparing symbolic numbers extends to non-symbolic materials which would (i) support the idea of a common system for processing/representing symbolic and non-symbolic numerical magnitudes and its spatial nature, and (ii) assess the extent to which a working memory interpretation better accounts for the data. Patients with and without left neglect and healthy controls were tested in two numerical comparison tasks, using Arabic digits or sequences of flashed dots. Given prior studies using numerical comparison, a distance effect (i.e., an increase in the response latencies and/or the error rates as the numerical distance between the numbers being compared decreases; Moyer & Landauer, 1967) is expected for both symbolic and non-symbolic inputs in control groups. Neglect patients are expected to be slower in symbolic number comparison task when responding to digits that are just smaller than the standard (i.e., in the number range from 1 to 9 and for a given reference of 5, digit 4 should be more difficult to process for the neglect group). Thus, particular attention will be devoted to performance on numerical magnitudes close to the standard on both sides of the standard. If this difficulty is attributed to an impaired access to the numerical representation on the relative left of the standard value on an input-independent spatial magnitude representation system, a similar pattern should arise both in symbolic and non-symbolic numerical comparison tasks. An absence of spatial-numerical bias in the non-symbolic task in neglect patients would challenge the hypothesis of a common spatial representation of symbolic and non-symbolic numerical magnitude. Working memory capacities of each group will be compared to evaluate if verbal working memory deficit accounts for the spatial-numerical bias in the neglect group.

2. Methods

2.1. Participants

Fourteen patients with left-unilateral spatial neglect following right posterior hemispheric damage (hereafter N+; mean age: 58 ± 11 years, 4 females, 13 right-handed) and eleven patients showing no sign of neglect (hereafter N−; mean age: 60 ± 11 years, 3 females, all right-handed)[2] participated in this study after giving written informed consent. All the patients had suffered from a right cerebral lesion at least three months previously; demographical and clinical details are listed in

[2] Two participants of the N- group had right brain lesions consecutive to a traumatic brain injury whereas all the other patients suffered from vascular lesions. It is however worth noting that withdrawing the data of these two patients from the analyses did not modify any of the results.