Brain and Cognition 86 (2014) 116–123

Contents lists available at ScienceDirect

Brain and Cognition

journal homepage: www.elsevier.com/locate/b&c

Disruptions to number bisection after brain injury: Neglecting parts of the Mental Number Line or working memory impairments?

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ARTICLE INFO

Article history:
Accepted 10 February 2014
Available online 6 March 2014

Keywords:
Number bisection
Mental number line
Spatial attention
Verbal working memory

ABSTRACT

The aim of this study was to investigate the mechanisms underlying consistent directional number bisection bias in a chronic neuropsychological sample, not selected based on behaviour or lesion definitions. Patients completed a test battery that included measures of number bisection, line bisection, verbal working memory, visual-spatial working memory, egocentric neglect and allocentric neglect. Neither the neglect nor working memory measures were found to significantly correlate with number bisection. Furthermore, when outlier patients with very distinct number bisection biases were compared to patients who did not show any number bisection difficulties, no differences were found between the two groups on any of the other behavioural measures. We conclude that number bisection difficulties are not consistently based on any single deficit, be it neglect or working memory, and biases in number bisection should not be assumed to directly reflect problems in either of these areas.

1. Introduction

Our ability to understand numbers is undoubtedly one of the most useful skills we have developed. Consequently, it is important to evaluate how numbers may be represented in the brain, and how this representation may breakdown following brain damage. One critical piece of evidence concerning number representation is the SNARC effect (Spatial Numerical Association of Response Codes): the observation that people respond faster on tasks involving smaller numbers with their left hand and on tasks involving larger numbers with their right hand (Dehaene, Bossini, & Giraux, 1993). The SNARC effect has been taken as a crucial piece of evidence that numerical values are represented on a 'mental number line' (MNL), with smaller numbers coded to the left side of larger numbers in internal space (e.g. Dehaene et al., 1993; Nunez, 2011; Priftis, Zorzi, Meneghello, Marenzi, & Umilta, 2006) (although see: Nunez, 2011). Aside from the SNARC studies, the distance effect has been put forward as evidence supporting a spatially represented MNL. Moyer & Landauer (1967) first demonstrated this, by finding that people are quicker to tell which of two numbers is bigger when the distance between them is large compared to when it is small (Moyer & Landauer, 1967). However, we should note that this effect may also be explained by simple logarithmic compression in the neural representation of magnitudes, as documented in animal studies (Nieder & Miller, 2003) and need not contain a spatial component (see also computational models, e.g. Verguts, Fias, & Stevens, 2005).

The MNL representation can be likened to a perception of space, akin to our perception of a physical line. Loftus, Nicholls, Mattingley, and Chapman (2009) found that we tend to bisect a horizontal line slightly to the left of its midpoint suggesting an over-representation of the left side of space. Similarly, people also show a very slight leftward bias in mental number bisection.

Neuropsychological evidence for a MNL comes from studies of patients with unilateral neglect. Here it has been reported that patients who typically show a bias in bisecting real lines also show a similar directional bias in mental number bisection (Zorzi, Priftis, & Umilta, 2002). For example, bisecting a line to the right of its midpoint and judging the middle of a numerical interval to be greater than the true midpoint has been found in patients with right-hemisphere damage (Zorzi, Priftis, Meneghello, Marenzi, & Umilta, 2006). In addition, patients' bisection errors on both real lines and numbers have been reported to increase with longer lines/larger numerical intervals (Umilta, Priftis, & Zorzi, 2009). Furthermore, for both real lines and numbers a crossover-effect has been found to exist for short line lengths/numerical intervals, with right-hemisphere damaged patients in these cases instead crossing too far to the left (Zorzi et al., 2002).

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http://dx.doi.org/10.1016/j.bandc.2014.02.004
0278-2626/

The relations between mental number bisection and spatial biases such as unilateral neglect are controversial however. Doricchi, Guariglia, Gasparini, and Tomaiuolo (2005), for example, found that performance on real line and MNL bisection was unrelated in patients showing visual neglect, suggesting that the two biases are doubly dissociated. Nevertheless, the authors noted that the neglect patients showing a number bisection bias all possessed right-hemisphere prefrontal damage, which is commonly associated with working memory problems. Doricchi et al. (2005) concluded that damage to prefrontal-cortex may cause problems in retaining contralateral spatial positioning in working memory and that this disrupts performance using the MNL. Umilta et al. (2009) pointed out that the number bisection bias has been found in patients without right prefrontal damage, though they do not support this with direct anatomical evidence. Overall, available evidence suggests that the number bisection bias is most frequently linked to lesions in the prefrontal rather than parietal number module (see Aiello et al., 2012; Doricchi et al., 2009, though note Pia, Corazzini, Folegatti, Gindri, & Cauda, 2009). Umilta et al. (2009) also note that the double dissociation detailed above is "not surprising" (p. 563) given that the line bisection task involves perceptual representation and number bisection involves mental representation. However, these distinct forms of representation have been previously shown to doubly dissociate in neglect patients (Anderson, 1993; Guariglia, Padovani, Pantano, & Pizzamiglio, 1993). This does not discredit the claim that the MNL is spatially represented in the same way that we represent a physical line (Zorzi et al., 2002, 2006), but it does reiterate that these two activities do not rely on the same brain structures. Overall, it seems that in patients with right hemisphere damage, neglect and number bisection do dissociate .

More recently, Aiello et al. (2012) demonstrated that right hemisphere lesion patients with a number bisection bias towards higher numbers than the midpoint demonstrate the same bias when the numbers are laid out on a clock face, (i.e. from right to left on a mental layout). This suggested that the bias may be more to do with the abstract size of the magnitudes than the spatial similarities in a left to right organised MNL. The alternative hypothesis put forward is that the right hemisphere is instrumental in the abstract representation of small numbers and it is damage to these networks that is causing the bias towards the larger numbers. This idea has received further support from a recent lesion-symptom analysis on number bisection which included both left and right hemisphere damage patients (Woodbridge, Chechlacz, Humphreys, & Demeyere, 2012).

In contrast to this small number hypothesis, van Dijck, Gevers, Lafosse, Doricchi, and Fias (2011) studied a patient, GG, who showed right neglect following a left-hemisphere lesion. GG displayed a strong leftward bias when bisecting both physical lines and mental images, yet showed a rightward bias in number bisection. This double dissociation appears to discount both perceptual and mental representational forms of neglect as being responsible for the number bisection bias. Furthermore, although GG's spatial working memory was intact she possessed verbal working memory difficulties. The authors hypothesised that GG's struggle with retaining the early numbers in a sequence meant that the initial sections of numerical intervals presented to GG were not represented within her MNL, thus resulting in an apparent rightward bisection bias.

van Dijck and Fias (2011) also found that when normal participants were required to memorise a list of numbers presented in random numerical order they later responded quicker with their left-hand to the numbers presented first in the list and faster with their right-hand to the numbers presented last. It was concluded that it is the position numbers are encoded in working memory that has a spatial reference rather than its actual numerical value. This implies that the MNL is a variable representation created by working memory to include numbers relevant to a specific task rather than a permanent store of numbers in long-term memory.

The current conflicting literature means that the direct cause behind the number bisection bias remains debateable. In the present study we examined the role of both spatial attention and working memory in number bisection by assessing an unbiased range of neuropsychological patients, not selected by either lesion site or behavioural profile, across an extensive test battery. The starting point and focus for this study is the behavioural performances and their correlations. However, the underlying lesion data can inform the theoretical understanding of the mental number line, and how it is accessed during number bisection. Each patient's number and line bisection skills were assessed along with their working memory and neglect level. By assessing patients both with and without neglect we were able to establish whether or not neglect is critical to generate biases in mental bisection of number, and/or whether variations in visual and verbal working memory are also necessary.

2. Method

2.1. Participants

Twenty-six patients with chronic brain injury (>9 months post injury) completed the experiment after giving informed consent. Their ages ranged between 39 and 79 years ($M = 64.5$, $SD = 11.9$), two were female. Patients were recruited from a voluntary panel at the University of Birmingham and collectively presented with a wide range of deficits. Selection was made at random, and the experimenter was blind to the patients' behavioural impairments and lesion sites at the time of testing. We did not have detailed scans for all of these patients (often due MRI incompatibility), and will therefore only discuss lesions in terms of gross descriptive terms. An overview Table of the patient's clinical and demographic details is given in Table 1.

2.2. Measures

Our test battery included measures of the six following features; number bisection, visual-spatial working memory, verbal span, verbal working memory, line bisection, and neglect.

2.2.1. Number bisection

The method used to assess number bisection was similar to that used by Zorzi et al. (2002). Number pairs were created with a range of three, five, seven or nine and were visually presented either in units, teens or the first tens (e.g. 1–3, 1–5…21–27, 21–29), each pair was also presented in reverse (e.g. 3–1) making a total of 24 possible pairs. In each block each of the 24 possible pairs was presented twice and at random. Patients completed three blocks in total, encompassing 144 numerical intervals with 72 presented in ascending order and 72 presented in descending order.

Each stimulus pair was presented to the patients for 5000 ms as two numbers positioned closely to either side of a central fixation point. In addition to this visual presentation, the examiner read out the numbers to the participant. This double mode of input and the length of the presentations were chosen to ensure that all participants correctly understood the endpoints of the interval (irrespective of visual/neglect problems or very short verbal spans). The patients were instructed to give the midpoint of the numerical interval without making calculations and to report their answer to the experimenter. Answers falling outside the range presented were not included in analysis.