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

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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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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.

Table 1
Patient overview: clinical and demographic details. Time post lesion (in years), Gross Lesion classification and Initial clinical deficits.

ID	Sex	Age	Handed.	Aetiology	Time post lesion (years)	Lesion classification	Initial deficits
1	m	76	Right	Stroke	3	Right superior temporal	STM deficit
2	m	78	Left	Stroke	14	Left frontal	Executive and verbal STM deficit
3	f	58	Right	Stroke	15	Left occipito-temporal	Alexia and right hemianopia
4	m	70	Right	Stroke	4	Left occipito-temporal	Right extinction
5	m	76	Right	Stroke	10	Left temporo-parietal	Dysphasia and right extinciton
6	m	22	Left	Stroke	12	Bilateral temporal	Dysexecutive and semantic deficits
7	m	85	Right	Anoxia	13	Left parietal	Amnesia and right extinction
8	m	45	Right	Encephalitis	15	Bilateral frontal + ACC	Amnesia, dysexecutive deficits and category specific recognition impairment
9	M	47	Right	TBI	3	Right sub-cortical	No major impairment
10	m	63	Right	Stroke	3	Right occipital	Left hemianopia
11	m	57	Right	Stroke	5	Right parietal	Left neglect
12	m	79	Right	Stroke	4	Right internal capsule	Executive dysfunction
13	m	71	Right	Stroke	2	Right putamen	STM problem
14	m	79	Right	Stroke	3	Left temporal	Dysphasia and right extinciton
15	m	51	Right	Stroke	5	Right temporal	Category specific recognition impairment
16	m	77	Right	Stroke	2	Right occipito-parietal	Left neglect
17	m	64	Left	Stroke	12	Right temporo-parietal	Left neglect
18	m	57	Right	Anoxia	10	Left parietal	Optic ataxia and right extinciton
19	m	39	Left	Stroke	10	Left temporal	Dysphasia and right extinciton
20	f	62	Right	Stroke	13	Bilateral parietal	Left extinction
21	m	56	Right	Stroke	4	Right fronto-parietal	Left neglect
22	m	77	Left	Stroke	8	Left temporo-parietal	Right extinction and STM deficit
23	m	67	Right	Stroke	2	Right temporo-parietal	Left neglect
24	f	54	Right	Stroke	2	Right occipital	Left hemianopia
25	m	63	Left	Stroke	2	Right cerebellum	Left extinction
26	m	73	Right	Stroke	8	Right temporo-parietal	Left neglect

Table 2
Overview of patient results on all tasks. The Corsi and digit span denote the largest sequence where 2/3 presentations were correct. The absolute line bisection is the average deviation from the middle over 10 lines bisected. Egocentric asymmetry and allocentric asymmetry from the Apples test, with negative values denoting right inattention and positive values left neglect. Number bisection values are average deviation from the middle. The one back value is an accuracy measure reflecting percentage correctly identified one back targets.

ID	Corsi span	Line bisection absolute	Egocentric asymmetry	Allocentric asymmetry	Number bisection	Digit span	One back
1	4	−0.98	1	0	0.525	5	94.59
2	4	0.37	1	−1	−0.8	4	72.97
3	3*	−0.21	−1	−1	0.035	8	75.68
4	4	0.3	4*	0	−0.1075	6	94.59
5	4	0.17	0	0	0.9825	4*	67.57
6	1*	−0.23	3*	0	0.46	3*	0
7	3*	0.22	1	1	0.9225	4*	81.08
8	4	0.19	−1	0	0.05	5	86.47
9	6	0.4	−2	0	−0.0825	5	100
10	4	−0.25	0	0	0	7	78.38
11	4	−0.1	0	1	0.07	5	100
12	4	−0.3	2	6*	0.08	6	64.86
13	3*	−0.02	1	1	0.0075	5	89.12
14	3*	0.38	5*	5*	0.005	5	78.38
15	4	0.18	0	0	−0.065	1*	89.19
16	5	0.99	2	0	−0.0825	6	67.57
17	3*	0.57	13*	0	0.4225	5	97.3
18	2*	−1.4	0	0	−0.2825	5	73
19	3*	−0.12	0	0	−0.18	1*	94.59
20	2*	−0.61	0	1	−0.21	4*	64.86
21	6	−0.64	−2	0	−0.345	6	78.38
22	5	−0.44	0	−2*	0.5175	2*	83.78
23	5	−2.07	11*	15*	−0.0075	4*	78.38
24	6	0.3	0	0	−0.035	6	100
25	3*	0.31	−3	0	0.03	4*	72.97
26	1*	−1.97	18*	8*	0.19	7	67.57

* Scores denote a clinical impairment.

For each number pair the correct answer was subtracted from the patient's answer meaning a negative result reflected a leftward deviation from the midpoint number and a positive result a rightward deviation. Each patient's average deviation overall over all numerical interval sizes is reported in Table 2.

2.2.2. Visuo-spatial working memory

A Corsi span was deduced for each patient using a traditional Corsi block tapping task (Corsi, 1972). For each sequence length, there were 3 random block sequence trials. The span reported in Table 2 is the highest sequence where a minimum of 2 out 3 trials were correct.

2.2.3. Verbal span

Patients heard three numbers read out (via a computerised voice) at 1000 ms intervals that they had to repeat back to the experimenter in correct order. This procedure was repeated three times (with different numbers), if the patient was successful on at least two out of three attempts then the list length increased by one number on the next trial, if not it decreased by one. This pattern continued with the maximum number of numbers the list could contain being seven. Once the patient twice failed to recall two out of three number lists of a set length the experiment ended. The patient's digit span was classed as the highest sequence with a minimum of 2 out of 3 correct (see Table 2 for values per patient).

2.2.4. Verbal working memory

Patients completed a version of the one-back task that involved 90 letters appearing one at a time for 500 ms in place of a central fixation cross at 3000 ms intervals (3×30 letter blocks). The instructions were to press the space bar whenever an identical letter to the one presented immediately before. There was a total of 30 targets, the percentage correct for each individual patient is reported in Table 2.

2.2.5. Line bisection

Horizontal lines of length 7.5 cm, 12.7 cm, 17.8 cm, 20.6 cm and 23 cm were presented on A4 paper placed centrally in front of the patients. Patients were instructed to mark the midpoint of each line. Each line length was presented twice to each patient, on one occasion presented to the left of the page's centre and on the other to the right, making a total of ten lines to be bisected by each patient.

The distance to the patients' mark was measured from the left end of the line. The actual midpoint of the line was subtracted from this distance meaning a negative result reflected a leftward deviation and a positive result a rightward deviation. Average bisection values per patient over these 10 lines are given in Table 2.

2.2.6. Neglect

The Apples Test (Bickerton, Samson, Williamson, & Humphreys, 2011) was administered to each patient once in order to determine their level of allocentric and egocentric neglect. Negative values denote a leftward bias (indicative of right neglect), Positive values denote a rightward bias (indicative of left neglect). Scores are given in Table 2, with starred scores denoting a clinical impairment (based on the BCoS control sample cut off scores).

2.3. Procedure

Due to the varying deficits and level of impairment of each patient, each required a different number and length of sessions in order to complete the test battery. Every session however was conducted in a quiet room and during all computer tasks the patients were positioned centrally approximately 50 cm away from the screen. The patients completed the measures in random order. For each task the same instructions were read out; if the patient did not understand then a further explanation was given.

3. Results

Potentially patients may have falsely demonstrated a number bisection bias through lack of understanding or ability to complete the task. For example, rather than attempting number bisection patients may have simply named the number that appeared to one side of the central fixation cross, a difference in performance under ascending and descending presentation conditions would reflect this. Twenty-six two-tailed paired-samples t-tests were therefore conducted comparing each patient's average deviations for each interval size under ascending and descending conditions, no significant differences were found. Consequently, all patients were included in further analysis.

For comparative analysis a single value representative of each patient's performance on each measure was calculated where possible. For the Corsi span and digit span this is the maximum length of sequence the patient could repeat reliably (2 out of 3 presented). For the Apples test each patient was given an egocentric score and an allocentric score (Bickerton et al., 2011). For the one-back task the patients were given a percentage score based on how many repetitions they correctly identified from the total number of targets. For the line bisection task each patient's average deviation overall was calculated based on their average deviation for each line length. Similarly, for number bisection each patient's average deviation overall was calculated based on their average deviation for each numerical interval size. Patients'scores on all these measures can be found in Table 2.

Using the data transformed as outlined above, Pearson's correlation analysis was used to deduce any relationships present between the measures (Table 1). As only some of the measures contained both positive and negative scores, all the values were made positive to ensure any relationships would likely be linear. Number bisection did not significantly correlate with any of the other test battery measures (Fig. 1). However, significant relationships did exist between egocentric neglect and line bisection ($r = .66$, $N = 26$, $p < .01$), allocentric neglect and line bisection ($r = .67$, $N = 26$, $p < .01$), egocentric neglect and allocentric neglect ($r = .62$, $N = 26$, $p < .01$), and between the Corsi span and one-back task ($r = .52$, $N = 26$, $p < .01$) (see Table 3).

The group was split into leftward and rightward number bisection deviators based on each patient's mean deviation direction. From the mean deviation and standard deviations of each group, we depicted with 95% certainty the range between which the general neuropsychological population's mean deviation would fall. Six patients within our sample demonstrated a mean number bisection bias which fell outside this confidence interval. To provide comparison, six patients from our patient group with consistent deviations closest to zero were selected to act as controls. Subsequently, a split-plot ANOVA with one between-participants factor (group: bias patients, non-bias patients) and one within-participants factor (interval size: 3, 5, 7, 9) was conducted to compare the effect of numerical interval size on number bisection performance between the two groups. This revealed a significant main effect of interval size ($F(1.39, 13.93) = 14.23$, $p < .01$, partial $n^2 = .59$) and of group ($F(1, 10) = 37.38$, $p < .01$, partial $n^2 = .79$). Furthermore, a significant interaction between group and interval size was revealed ($F(1.39, 13.93) = 11.69$, $p < .01$, partial $n^2 = .54$), suggesting overall that the rate that the larger numerical intervals caused the number bisection bias to increase was greater in the bias than in the control group (see Fig. 2). Of note is that 2 of the patients in this group exhibited a negative bias, meaning they

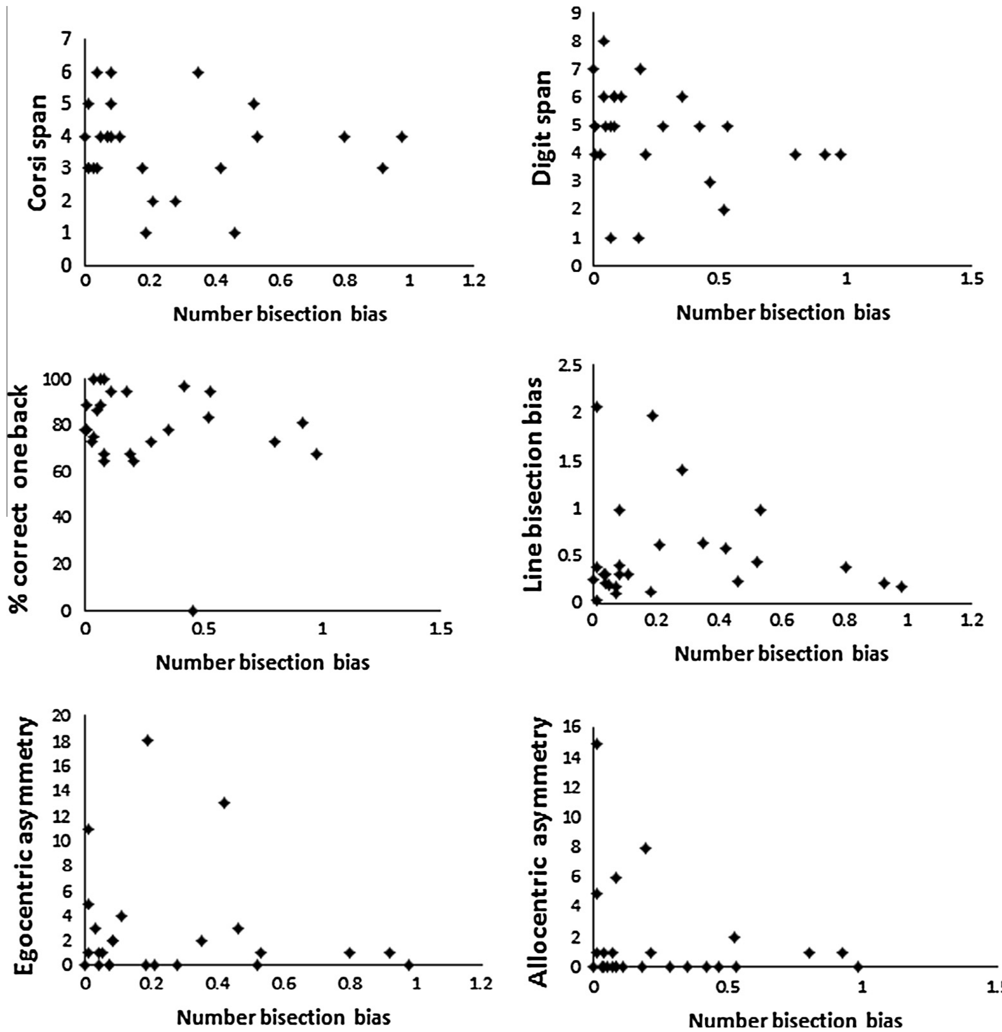

Fig. 1. Scatter plots displaying the relationship between number bisection and other test battery measures. From top left, row by row, scatter plots between the number bisection bias and (i) Corsi span, (ii) verbal digit span, (iii) one back performance, (iv) line bisection bias, (v) egocentric and (vi) allocentric asymmetry scores.

Table 3
Correlations (with corresponding significance levels) between the test battery measures.

	Corsi block	Line bisection	Egocentric neglect	Allocentric neglect	Number bisection	Digit span
Line bisection	$r = -.11$					
	$p = .58$					
Egocentric neglect	$r = -.29$	$\mathbf{r = .66}$				
	$p = .15$	$\mathbf{p < .01}$				
Allocentric neglect	$r = -.04$	$\mathbf{r = .67}$	$\mathbf{r = .62}$			
	$p = .86$	$\mathbf{p < .01}$	$\mathbf{p < .01}$			
Number bisection	$r = -.10$	$r = -.07$	$r = -.10$	$r = -.21$		
	$p = .62$	$p = .73$	$p = .62$	$p = .30$		
Digit span	$r = .07$	$r = .20$	$r = .24$	$r = .09$	$r = -.29$	
	$p = .74$	$p = .33$	$p = .23$	$p = .68$	$p = .16$	
Verbal working memory	$\mathbf{r = .52}$	$r = -.10$	$r = -.07$	$r = .10$	$r = -.22$	$r = .06$
	$\mathbf{p < .01}$	$p = .64$	$p = .75$	$p = .64$	$p = .29$	$p = .76$

responded with numbers lower than the midpoint, whereas the 4 other patients in the bias group demonstrated a positive bias.

Subsequently, six independent-samples two-tailed t-tests comparing the performances of the bias and control group on each of the other test battery measures were conducted. For line bisection and the Apples test all scores were made positive to avoid leftward and rightward deviations cancelling each other out. The results revealed no significant differences between the groups across the six measures (Fig. 3).

4. Discussion

The primary aim of our investigation was to identify the relations between the number bisection bias and variations in spatial

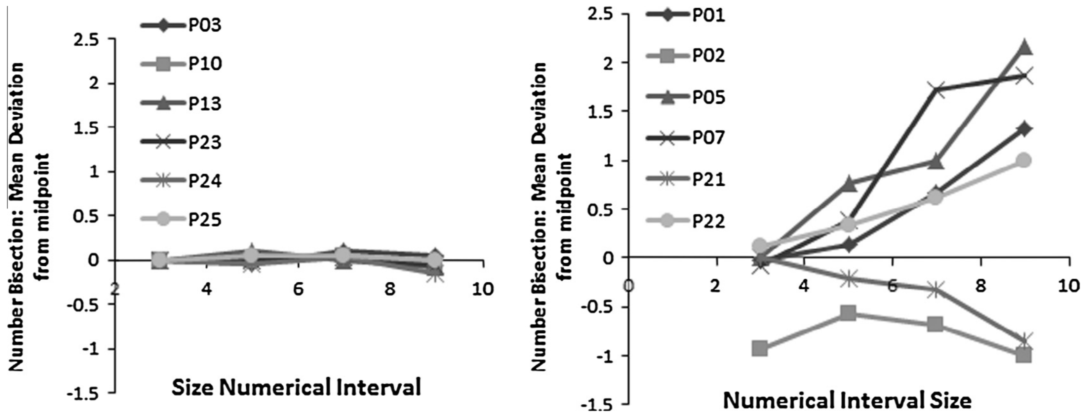

Fig. 2. *Right*: 6 Outlier patients' number bisection bias as a function of interval size. *Left*: control group with no number bisection bias.

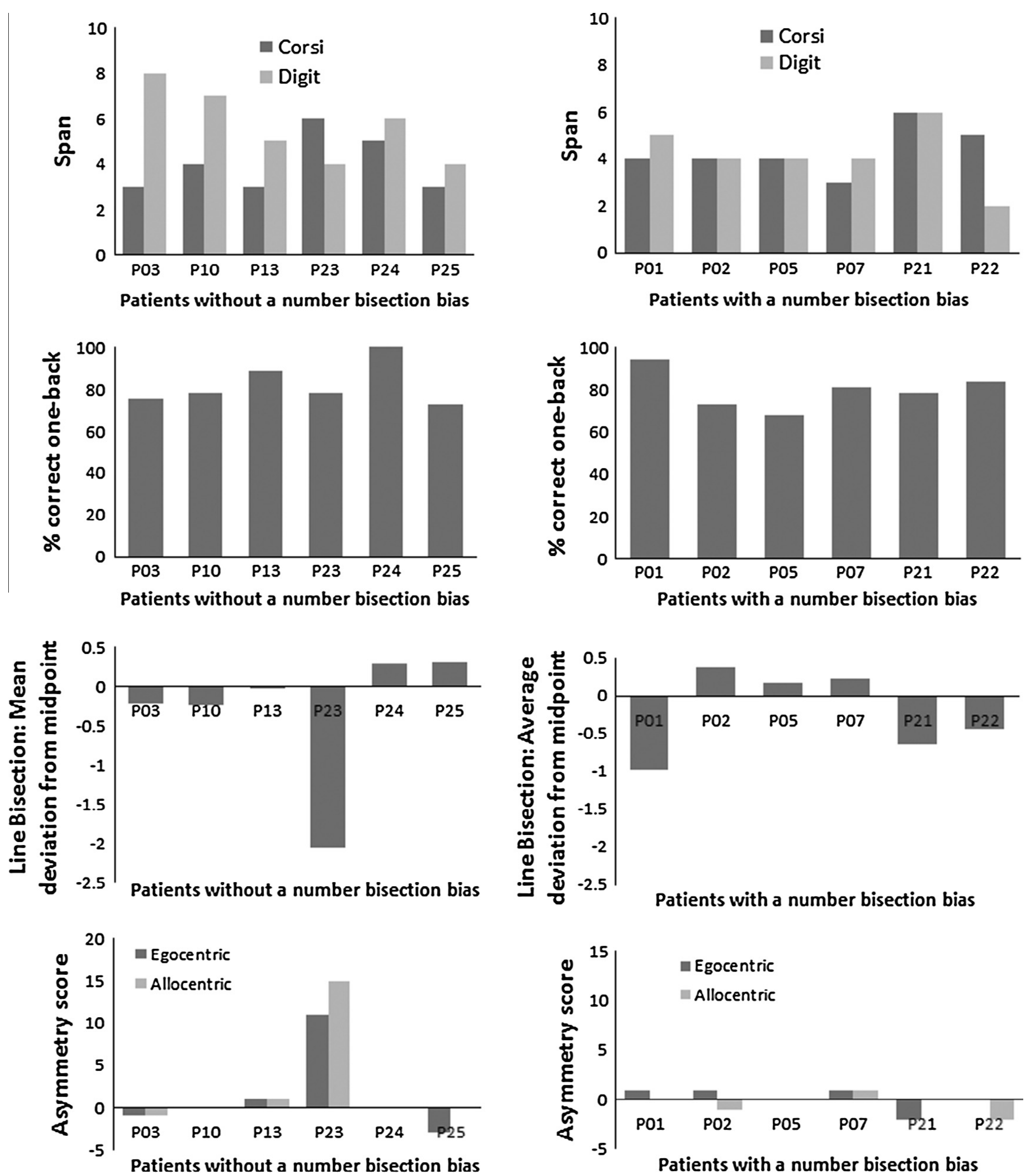

Fig. 3. Comparison of performances of number bisection bias group and non bias group patients across all test measures.

attention and working memory in an unselected neuropsychological population, irrespective of lesion site or behavioural profile. We found evidence for some relation between biases in line bisection and neglect. Egocentric and Allocentric neglect scores were positively related to line bisection suggesting that, as neglect gets worse, so the line bisection bias increases. However, there was no evidence to suggest that number bisection is related to line bisection or indeed the more direct measures of neglect. Though prior studies examining the relations between neglect and number bisection have used line bisection as their measure of neglect (Zorzi et al., 2006). Doricchi et al. (2005), however, reported a double dissociation between the line and number bisection bias. In addition, Pia et al. (2012) confirmed functional independence between physical visual space and number bisection. Indeed, in our data there is also clear evidence of a double dissociation. For example, patient 22, was included in our number bisection bias group yet showed no sign of a line bisection bias. Furthermore patient 23 possessed the strongest line bisection bias within our patient sample but showed no such bias in number bisection. Therefore, our results, like those of Doricchi et al. (2005) and Pia et al. (2012), suggest that number and line bisection do not tap the same critical mechanisms.

When considering the 6 patients whose number bisection bias was so strong, it fell outside of the group's range, there was no difference in performance on any of the neglect measures between this bias and a control group distinguished on the basis of their number bisection performance we conclude that neglect is by no means a prerequisite to a number bisection bias.

In contrast to the results between the neglect measures and number bisection, there were systematic relations between the different neglect measures (ego- and allocentric neglect measured on the Apples test and line bisection). Previous studies have reported some dissociations between ego- and allocentric neglect (e.g. Chechlacz et al., 2010), whilst line bisection biases have been argued to be closely linked to egocentric neglect (Chechlacz et al.; Verdon et al., 2010). It is possible that the current correlations reflect patients with damage around the temporo-parietal junction, since it has also been noted that damage to that region can lead to both egocentric and allocentric neglect (Chechlacz et al., 2010).

There was also a reliable correlation between the visual working memory task (Corsi blocks) and the verbal working memory (one-back) task. This is consistent with both tasks being dependent on executive functions to help maintain information (cf. Baddeley, 1986). In contrast, neither of these tasks correlated with verbal digit span. This is to be expected if digit span is primarily dependent on a relatively modular phonological loop, separated from other executive control processes. More critically, none of the memory measures related to MNL errors. There was no support for the argument that memory maintenance is a vital component of number bisection. Consistent with this we also failed to find any patient who showed opposite number bisection biases dependent on whether numbers were presented in ascending or descending order. There was also no difference in any of the measures of memory between the bias and control group meaning we again conclude that impairments in memory are not a driving factor for poor mental number bisection.

Some may argue that although our bias group showed no sign of perceptual neglect, neglect of mental images may have caused their number bisection bias especially given that the MNL is represented in mental space. However, for a patient to suffer from representational neglect without any perceptual spatial deficits is rare (Bartolomeo, Derme, & Gainotti, 1994), making this highly unlikely to be the case for all six patients. Moreover, van Dijck et al. (2011) found that their patient showed a number bisection bias in the direction opposite to her representational neglect.

It seems that the final hypothesis of a number specific problems, perhaps relating to differing representations of small and larger numbers may be in keeping with our findings. Aiello, Merola, and Doricchi (2013) found that in a group of right hemisphere damaged patients number bisection biases were only present for number intervals taken from the first decade, i.e. to intervals that include the smallest number magnitudes.

When addressing the lesion question, if we regard the number bisection bias group, there was no clear single underlying lesion site, even with respect to side of lesion (2 right side lesions, 4 left – unrelated to positive or negative bias). Though only a basic subdivision of lesion sites was used here, it is clear that there was no single consistent lesion site associated with a deficit in number bisection. Different lesions which, here, gave rise to a number bias included left inferior frontal, right temporo-parietal, left temporo-parietal, left parietal only and right superior temporal lesions. From this, it appears that multiple components can contribute to an impaired performance in number bisection. Future research in a large variety of patients could try to disentangle these components further using a more elaborate set of tasks, investigating the different possible reasons for number bisection bias, other than the spatial attention and working memory components addressed in this study.

In conclusion, undoubtedly we have identified several patients within a widely varied neuropsychological sample that possess a number bisection bias. For both past literature and the present study the focus has been on finding a global impairment in spatial-attention or working memory that could explain this phenomenon. In agreement with previous studies, we suggest that a number bisection bias is not occasionally dissociated from spatial neglect, but rather may be systematically dissociated. We speculate that multiple components can contribute to impaired number bisection, including perhaps a more localised deficit directly involving numbers.

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