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The line bisection bias as a deficit of proportional reasoning – evidence from number line estimation in neglect

S. Smaczny [a], E. Klein [b,c], S. Jung [c,d,e], K. Moeller [c,f,g], H.-O. Karnath [a,h,*]

[a] Centre of Neurology, Division of Neuropsychology, Hertie-Institute for Clinical Brain Research, University of Tuebingen, Tuebingen, Germany
[b] University of Paris, LaPsyDÉ, CNRS UMR8240, La Sorbonne, Paris, France
[c] Leibniz Institut Fuer Wissensmedien, Tuebingen, Germany
[d] Department of Computer Science/Therapy Science, Trier University of Applied Science, Trier, Germany
[e] Institute for Cognitive & Affective Neuroscience (ICAN), Trier University, Trier, Germany
[f] Centre for Mathematical Cognition, School of Science, Loughborough University, United Kingdom
[g] LEAD Graduate School and Research Network, University of Tuebingen, Tuebingen, Germany
[h] Department of Psychology, University of South Carolina, Columbia, SC, USA

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ABSTRACT

This study aimed to investigate whether neurological patients presenting with a bias in line bisection show specific problems in bisecting a line into two equal parts or their line bisection bias rather reflects a special case of a deficit in *proportional reasoning* more generally. In the latter case, the bias should also be observed for segmentations into thirds or quarters. To address this question, six neglect patients with a line bisection bias were administered additional tasks involving horizontal lines (e.g., segmentation into thirds and quarters, number line estimation, etc.). Their performance was compared to five neglect patients without a line bisection bias, 10 patients with right hemispheric lesions without neglect, and 32 healthy controls. Most interestingly, results indicated that neglect patients with a line bisection bias also overestimated segments on the left of the line (e.g., one third, one quarter) when dissecting lines into parts smaller than halves. In contrast, such segmentation biases were more nuanced when the required line segmentation was framed as a number line estimation task with either fractions or whole numbers. Taken together, this suggests a generalization of line bisection bias towards a segmentation or proportional processing bias, which is congruent with attentional weighting accounts of line bisection/neglect. As such, patients with a line bisection bias do not seem to have specific problems bisecting a line, but seem to suffer from a more general deficit processing proportions.

1. Introduction

Following a (predominantly) right hemispheric stroke, patients often develop spatial neglect, a deficit whereby patients shift their visual orientation towards the ipsilesional side, potentially ignoring objects presented contralesionally. Some patients with spatial neglect show difficulties correctly bisecting a visually presented horizontal line. Instead of indicating the correct midpoint of the line, they typically mark a point that deviates to the right of the true midpoint (e.g., Ferber and Karnath, 2001; McIntosh et al., 2005). One interpretation of this line bisection bias has been an asymmetry of lateralised attention allocation (i.e., an attentional bias) between the left and the right hemisphere (Kinsbourne, 1987). According to this account, neglect patients allocate more attentional resources to the right as compared to the left side of the line. In turn, this leads to the observed rightward bias in their bisection of the line. A more recent attentional weighting model of line bisection proposed by McIntosh et al. (2005) suggests that correct line bisection is dependent on a balanced attentional weighting of both endpoints to identify their midpoint. In patients with neglect, attentional weighting is assumed to be imbalanced so that the right endpoint is over-weighted, which leads to the rightward bisection bias.

Evidence for this model comes from an endpoint reproduction task (Abe and Ishiai, 2022), in which patients with neglect bisected lines of different lengths (5, 10, and 20 cm) on a tablet. After the bisection the lines disappeared from the screen and patients had to indicate either the position of the line's left and right endpoint. While the right endpoint

* Corresponding author. Centre of Neurology, Division of Neuropsychology, Hertie-Institute for Clinical Brain Research, University of Tuebingen, Tuebingen, Germany.

E-mail address: karnath@uni-tuebingen.de (H.-O. Karnath).

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was placed accurately (with no significant difference to healthy controls), patients could not reliably reproduce the position of the left endpoint. Instead, they marked the same position as the left endpoint irrespective of line length. Moreover, there are models suggesting a non-linear gradient of attentional weighting. For instance, Anderson (1996) proposed a mathematical model formalizing different attentional weighting for the left and right hemisphere in neglect to be the underlying process in line bisection bias. The right hemisphere can allocate attention in a balanced way across the left and right side of space, whereas the left hemisphere is assumed to allocate attention only to the right side of space. When the right hemisphere is lesioned, a rightward attentional bias (neglect) occurs.

Interestingly, spatial neglect was also observed to affect the representation of number magnitude. For instance, in verbal number bisection (e.g., what is the midpoint between 1 and 9) patients were observed to exhibit a rightward bias similar to their line bisection bias (i.e., indicating 6 as the midpoint between 1 and 9, cf. Zorzi et al., 2002; Priftis et al., 2006; but see Doricchi et al., 2005). This has been interpreted to corroborate the notion of a *mental number line* reflecting a spatial representation of number magnitude with smaller magnitudes associated with the left side of space and larger magnitudes with the right (e.g., Dehaene et al., 1993, see als Umiltà et al., 2009 for a review of evidence on the spatial representation of number magnitude from neglect).

Importantly, one task often used to assess spatial representations of number magnitude is very similar to Line Bisection. In particular, in Number Line Estimation (NLE) participants have to locate a given number upon a number line of which only the endpoints are given (e.g., where does 63 go on a number line ranging from 0 to 100). Psychophysical models of number line estimation (NLE) in healthy adults and children have been formalised (e.g., Barth and Paladino, 2011; see Dackermann et al., 2018 for an overview). These typically indicate that with increasing age and expertise for a specific number range participants rely increasingly on reference points (i.e., start, end-, and midpoint) to calibrate their number line estimation (e.g., 63 is a bit right of the spatial middle of the line). Based on this, it has been argued that number line estimation is typically performed by applying proportional reasoning and thus non-numerical processes (for evidence in children: Barth and Paladino, 2011; Dackermann et al., 2018; Jung et al., 2020, and healthy adults: Chesney and Matthews, 2013; Reinert et al., 2015). Therefore, NLE may serve as an indicator of proportional reasoning instead of purely numerical estimation. That is, participants will orient their response according to specific landmarks on the line, such as the endpoints or the perceived midpoint, irrespective of the number range portrayed by the line. Therefore, number line estimation may be considered a generalization of line and number bisection tasks. Considering these similarities in conceptualisation, the question arises of what happens when patients presenting with a line bisection bias are explicitly required to apply proportional reasoning on a horizontal line.

In the study by Gallace et al. (2008), patients with neglect were presented with a 16 cm line as well as a sample line of 1, 2, 4, or 8 cm. They then had to divide the 16 cm line into accordingly sized segments (i.e., with the 4 cm sample they would dissect the line into four 4 cm segments). When patients had to dissect the line into two 8 cm segments, the authors observed that the left segment became significantly longer than the right — somehow resembling the bias typically observed in line bisection. However, there was no effect when neglect patients had to dissect the line into smaller segments, that is, dividing the line into quarters or even smaller segments. This implies that specifically bisecting (i.e., dissecting it into halves) seems challenging for some neurological patients. Instead, dissecting it into other proportions, such as quarters, may not. However, these results might also stem from the chosen methodology: While for the 8 cm sample neglect patients may have simply bisected the line, for shorter segments one might argue that neglect patients reproduced the sample lines onto the 16 cm line instead of segmenting it.

In a different study, Lee et al. (2011) had neurological patients mark either the left quarter (leftmost 25% of the line), the centre, or the right quarter of a line. Neglect patients were found to mark the right quarter significantly more to the right than non-neglect patients and healthy controls. However, there was no significant difference observed for the left quarter. As such, these findings seem to suggest that the increased attentional weighting of the right endpoint leads to an underestimation of line segments on the right (i.e., placing their mark too far to the right) while segments on the left were correctly estimated. This contrasts the findings of Abe and Ishiai (2022), who observed that the right end of the line was correctly represented while the left end was not. However, Lee et al. (2011) suggested that their findings may also stem from explicitly asking patients to draw their attention to either the left or right side, which may have provided a top-down 'override' of the bottom-up deficit defining neglect (Karnath, 2015). In Abe and Ishiai (2022), patients were asked to make their mark after the line had already vanished, thus not drawing their attention to any endpoint while the line was visible. Therefore, it may be feasible to use a task in which patients are not explicitly cued to either endpoint but examine the line as a whole such as number line estimation.

1.1. Study objectives

Accordingly, the current study aimed at evaluating whether bisection bias in neglect patients indeed reflects a specific problem in bisecting a line into two equal parts or rather a special case of a deficit in *proportional reasoning* more generally. In the latter case, the bias should also be observed for other segmentations (e.g., into thirds or quarters) and/or in number line estimation. Therefore, we administered four different line dissection tasks to (i) patients with neglect displaying a line bisection bias, (ii) patients with neglect not displaying this bias, (iii) patients with right hemisphere lesions without neglect, and to (iv) age-matched healthy control participants.

As a first task, all participants completed a typical *line bisection* task in order to have a baseline line bisection bias for the line length of the administered stimuli. In a second task, the *segmentation* task, neglect patients had to subdivide a line into four (the 'quarters' subtask) or into three equal parts (the 'thirds' subtask). They had to place all segmentation marks on the same line (different from Lee et al., 2011) and could freely choose the points (instead of being provided with a sample line to copy as in Gallace et al., 2008) to rule out attentional biasing to either endpoint of the line. This task allowed us to examine patients' spontaneous dissecting behavior of a line without cueing them to one side first, thus providing a more natural measure of how they process smaller proportions of the line and how this may differ from bisecting it.

Next, participants had to complete two NLE tasks. One on fractions and one on whole numbers. To keep these tasks comparable to the other tasks and not provide any perceptual cues, no flanking numbers were given on the line at the start and endpoint. Instead, participants were verbally instructed to imagine the line as the number range required for the task (i.e., 0–1 for the fraction and 0–10 for the whole number task). This enabled the comparison of purely visuo-spatial line segmentation and proportional reasoning applied to the spatial representation of number magnitudes.

Additionally, patients also completed a verbal number bisection task (e.g., "what is the middle number between 1 and 9?", equivalent to Zorzi et al., 2002). This was included as a control task requiring numerical segmentations in a modality different from horizontally presented lines to allow evaluation potential influences of presentation format.

2. Methods

2.1. Participants

Neurological patients consecutively admitted to the Centre of Neurology at Tuebingen University (Germany) and to the Ermstalklinik in Bad Urach (Germany) were screened for a first-ever right-hemisphere stroke. Patients with a left-sided stroke, patients with diffuse or bilateral brain lesions, patients with tumors, as well as patients in whom MRI or CT scans revealed no obvious lesions were not included.

Twenty-one patients with a unilateral, right-sided stroke without visual field defects participated in the study (cf. Table 1). Of these, 11 patients were diagnosed with spatial neglect, and ten were not (N-). According to finger perimetric testing, none of the patients presented with visual field defects. Patients that presented with neglect were further subdivided into a group of patients who showed a line bisection bias (NLB+) and those who did not (N+) (see procedure for details).

An age-matched (mean, SD) control sample of 32 healthy individuals was also recruited (HC). None of the healthy participants reported any neurological or psychiatric history, and all had normal or corrected-to-normal vision. All participants gave written informed consent to participate in the study. The study was carried out following the Declaration of Helsinki (2013) and was approved by the ethics committee of the University Hospital Tuebingen (Vote 82/2018 BO2).

2.2. Procedure

2.2.1. Clinical examination

All stroke patients were examined with the common neurological confrontation technique for visual field defect (please note that for this sample none of the patients showed signs of visual field defect). and were administered the following standard tests to diagnose neglect: Letter cancellation (Weintraub and Mesulam, 1988), Bells cancellation (Gauthier et al., 1989), a copying task (Johannsen and Karnath, 2004), and line bisection (as in Ferber and Karnath, 2001). All tests were presented on an A4 sheet of paper in landscape orientation. For a firm diagnosis of spatial neglect, patients had to fulfill the following criterion in at least two of the four tests.

In the *Letter cancellation* task, 60 target letters 'A' are distributed across the sheet of paper amid other distractor letters, and patients are asked to cancel out all target letters. The *Bells Cancellation Test* requires patients to identify 35 bell symbols distributed on a field of other symbols. For both the Letter Cancellation Task and the Bells Test, we calculated the Centre of Cancellation (CoC) using the procedure and software by Rorden and Karnath (Rorden and Karnath, 2010; www.mricro.com/cancel/). CoC scores larger than 0.08 in the Letter Cancellation Task and the Bells Test indicated neglect behavior (Rorden and Karnath, 2010).

Table 1
Demographic and clinical data of all participants.

	HC	N-	N+	NLB+
Age (years)	66.21 (6.93)	66.20 (13.98)	63.2 (14.25)	73.17 (7.96)
Sex F/M (NA)	16/14 (2)	3/7	2/3	1/5
Etiology (Ischemia/ Hemorrhage)	–	9/1	3/2	3/3
Lesion location:	–			
MCA territory	–	20%	100%	83%
MCA & PCA territory	–	10%	0%	0%
Basal Ganglia only	–	40%	0%	0%
Thalamus only	–	30%	0%	17%
Time since lesion (days)	–	4.5 (4.01)	62.8 (67.60)	25 (27.29)
Letter Cancellation (CoC)	–	0.014 (0.021)	0.534 (0.319)	0.515 (0.212)
Bells Cancellation (CoC)	–	0.020 (0 0.039)	0.579 (0.382)	0.496 (0.357)
Copying task (points)	–	0.5 (1.27)	3.6 (2.41)	3.83 (1.17)
Diagnostic line bisection[a] (% deviation from midpoint)	–	2.75 (6.10)	7.41 (6.71)	34.58 (23.94)

Data represent means with SD in parentheses.
[a] This line bisection task is the line bisection task used in the standard neglect diagnostic battery. It is not the same as the line bisection task considered in our analyses (*'experimental line bisection task'*).

In the *copying task*, patients were asked to copy a complex multi-object scene consisting of four figures (i.e., a fence, a car, a house, and a tree), two each in the left and right half of the test sheet. The following test scores were awarded depending on the correctness of the copied figure: The omission of at least one contralateral feature of each figure was scored 1 point. An additional point was awarded when contralaterally located figures were drawn on the ipsilesional side of the sheet. Omitting the complete figure was awarded 2 points. In sum, the maximum score was 8. A score higher than 1 (i.e., >12.5% omissions) indicated neglect (Johannsen and Karnath, 2004).

The *line bisection task* included 10 lines that were 24 cm in length and presented on individual sheets of paper. Lines were presented alternately towards the left or right side of the respective page. While cut-offs for line bisection can range from 4% deviation (Kinsella et al., 1995) to 20% (Marsh and Kersel, 1993), we wanted to ensure a robust presence of line bisection bias, and used a more conservative cut-off of 14% (also used in Ferber and Karnath, 2001). In addition, we also performed a second analysis using a more liberal cut-off of 6.5% (as used in Azouvi et al., 2002).

Finally, neglect patients were pooled into two separate group depending on whether they presented with a line bisection bias (NLB+) or not (N+).

2.2.2. Experimental tasks

Participants were always presented with the same stimuli for the experimental tasks: 20 cm long horizontal lines presented centrally on an A4 sheet of paper in landscape orientation with only one line per sheet of paper. Participants were explicitly instructed not to measure or, in the case of number lines, count to derive a solution. Instead, they were told to answer intuitively. Responses were measured to the closest mm.

In the *experimental line bisection task*, participants had to bisect 5 lines on separate sheets of paper.

In the *segmentation task*, they were required to divide the line into different numbers of equal segments: On five items each they had to dissect the lines into either 4 ('quarters task') or 3 ('thirds task') equally sized segments, in pseudo-randomized order. To ensure best task performance, participants were explained how many marks they had to set to divide the line into the correct number of segments in case participants did not understand the initial task instructions.

In the *fraction task*, participants were asked to imagine the presented line as a number line ranging from 0 to 1. The numbers themselves (i.e., 0 and 1) were not printed on the paper, as flanking numbers are known to affect the dissection of lines (e.g., De Hevia, Girelli and Vallar, 2006; Fischer, 2001). Participants then had to mark the spatial location of the fractions 1/4, 1/3, 1/2, 2/4, 2/3, and 3/4 on the number line (each number on an individual sheet of paper), five times each, in randomized order. This procedure yielded 30 trials in total.

The *whole number task* was conceptually identical to the previous task, with the only difference that the number line was indicated to range from 0 to 10 instead of from 0 to 1. Participants then had to indicate the spatial location of the numbers 1, 4, 5, 6, and 9 on the number line. Again, each number had to be estimated 5 times on separate pages, yielding 25 trials.

In the *verbal number bisection task* (see Zorzi et al., 2002), patients were presented with two numbers (ranging from 1 to 22) and had to respond promptly, without calculating, which number is the middle number between the two numbers given. Bisections were presented once in ascending order ("What number is exactly between 3 and 7?") and once in descending order ("What number is exactly between 7 and 3?"). This procedure yielded 44 trials in total.

2.3. Statistical analyses

As indicated above, participants' responses were measured in mm from the left end of the line. For each participant, mean and SD of responses were calculated for each mark (e.g., mean and SD of marks indicating the number '1' in the whole number task). These means were analysed using the non-parametric Kruskal-Wallis test to compare estimation performance across participant groups. In case a task included several measures (e.g., dissecting the line into three and four segments), each segment mark was analysed separately. For example, for the quarters subtask, we ran separate Kruskal-Wallis tests for the 1/4, 1/2, and 3/4 marks, respectively. All post-hoc tests were corrected using Benjamini-Hochberg corrected Dunn-Bonferroni tests; all reported *p*-values were adjusted for multiple comparisons.

3. Results

Descriptives for all tasks can be found in Table 2.

3.1. Experimental line bisection

One patient from the NLB + group did not complete this task and is not included in this analysis. Fig. 1 illustrates participants' deviation from the centre of the line in the line bisection task. As expected, there was at least one significant difference between two of the four groups as indicated by the Kruskall-Wallis test (H (3) = 14.728, p = 0.002). Post-hoc tests indicated a significant difference between the HC and the NLB + group (adj. p = 0.002), whereby patients with a line bisection bias showed a larger deviation from the centre as compared to healthy controls.

Table 2
Descriptive values for all groups and all tasks.

		HC	N-	N+	NLB+
LB		−0.17	0.26	0.67	2.60
		(0.32)	(0.69)	(1.77)	(2.17)
Quarters segmentations	1/4	−0.08	−0.22	0.55	4.45
		(0.26)	(0.57)	(1.20)	(3.48)
	2/4	−0.02	0.01	−0.21	2.58
		(0.27)	(0.66)	(1.42)	(1.94)
	3/4	0.10	0.21	−0.90	1.02
		(0.33)	(0.59)	(2.55)	(1.34)
Thirds segmentations	1/3	−0.25	−0.25	0.07	2.77
		(0.33)	(0.48)	(0.67)	(3.67)
	2/3	0.12	0.28	−0.12	2.23
		(0.36)	(0.60)	(1.62)	(1.92)
Fractions	1/4	−0.21	−0.02	−0.21	2.99
		(0.82)	(0.59)	(3.16)	(3.00)
	1/3	−0.05	0.20	−0.44	2.35
		(0.39)	(2.52)	(3.64)	(3.74)
	1/2	−0.04	0.11	−0.01	1.24
		(0.35)	(0.54)	(0.58)	(1.39)
	2/4	1.08	1.61	1.28	1.01
		(0.36)	(1.07)	(1.52)	(2.96)
	2/3	−0.35	0.70	−4.07	−2.50
		(0.81)	(1.17)	(3.34)	(4.64)
	3/4	−1.18	−1.73	−0.95	−2.83
		(0.53)	(1.60)	(1.62)	(2.57)
Whole Numbers	1	0.02	−0.52	−1.55	−0.57
		(0.61)	(0.53)	(0.50)	(1.70)
	4	−0.22	1.36	−0.19	0.89
		(0.41)	(3.85)	(0.79)	(1.06)
	5	−0.05	1.06	−0.64	1.32
		(0.31)	(2.80)	(1.01)	(0.79)
	6	−0.26	0.26	−0.42	0.43
		(0.43)	(2.50)	(0.71)	(0.66)
	9	−0.26	−0.12	1.07	0.57
		(0.40)	(0.84)	(0.73)	(0.47)
Verbal Number Bisection	(mean)	−0.03	−0.35	−0.23	−0.88
		(0.10)	(0.64)	(0.15)	(0.92)

Data reflect mean deviations in cm relative to the true value and (SD) of all groups for all tasks.

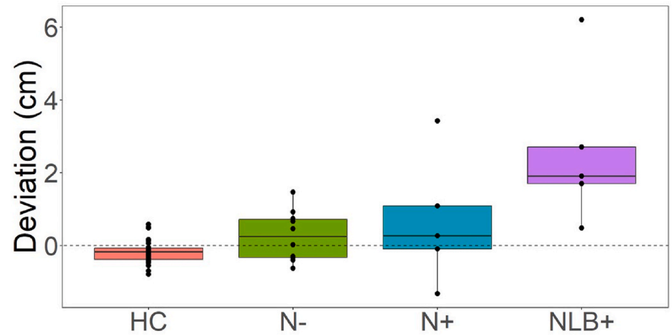

Fig. 1. Mean line bisection bias for each group. The y-axis represents participants' deviation from the centre of the line in cm. Positive values denote a rightward bias. Note that the outlier in group N+ was just under the cut-off of 14% in the diagnostic line bisection task to get classified as NLB+.

3.2. Segmentation

In the *segmentation* task, the same lines as used before in *the experimental line bisection task* were presented. However, now participants were required to dissect the line into either 4 ('quarters task') or 3 ('thirds task') equally sized segments. Seven patients showed difficulties carrying out this task correctly. Despite explaining how many marks they should make to arrive at the correct number of segments, they occasionally set one extra mark. In six of the seven patients, the respective trials were not considered in the analysis; one patient (P15) made too many marks on all trials and was not included in the analysis for this task.

Fig. 2 illustrates the difference between participant marks and the correct positions of corresponding marks for the 'quarters' subtask; Fig. 3 for the 'thirds' subtask. Table 3 presents the corresponding results of the accompanying Kruskal-Wallis tests, respectively. There was evidence for significant group differences in both subtasks: For the *quarters* task, the Kruskal-Wallis results indicated significant group differences for the two left lines (i.e., indicating the 1/4 and 1/2 segment of the line). Post-hoc tests revealed a significant difference between the NLB+ and HC group as well as the NLB+ and the N- group for the 1/4 mark. Additionally, there was a significant difference between the NLB + group and all other groups for the ½ line (all adj. $p < 0.05$). Participants from the NLB + group placed their marks significantly further to the right than groups HC and N- for the ¼ and all other groups for the ½ mark. For the rightward mark (2/3) of the 'thirds' task, groups also differed significantly. Patients from the NLB + group placed the 2/3 mark further to the right than those from the HC group (adj. $p < 0.05$).

Upon closer inspection, in the 'quarters' subtask, one N+ (P3) and two NLB+ (P12, P19) patients showed a response pattern indicating that they placed all three lines very close to one another instead of truly dividing the line into equal parts. Also, the same patient from the N+ group (P3) and a different patient from the NLB + group (P20) behaved very differently from the rest of their groups in the 'thirds' subtask (see Fig. 3). It seems that these patients could not solve the tasks correctly (see supplementary material for a more in-depth elaboration on these particular patients). Therefore, we assume that these patients may have used a different strategy. Consequentially, we re-analysed the data of the *segmentation task*, excluding the respective patients (see Table 4). In this re-analysis, Kruskal-Wallis tests for group differences were significant for all marks except for the 3/4 mark. In particular, we observed a significant difference between the NLB + group and all other groups for the 1/4 mark. We also observed a significant difference between the NLB+ and the HC group as well as the NLB+ and the N- group for the 1/2 mark (all adj. $p < 0.05$).

For the 1/3 mark of the 'thirds' subtask, the NLB + group

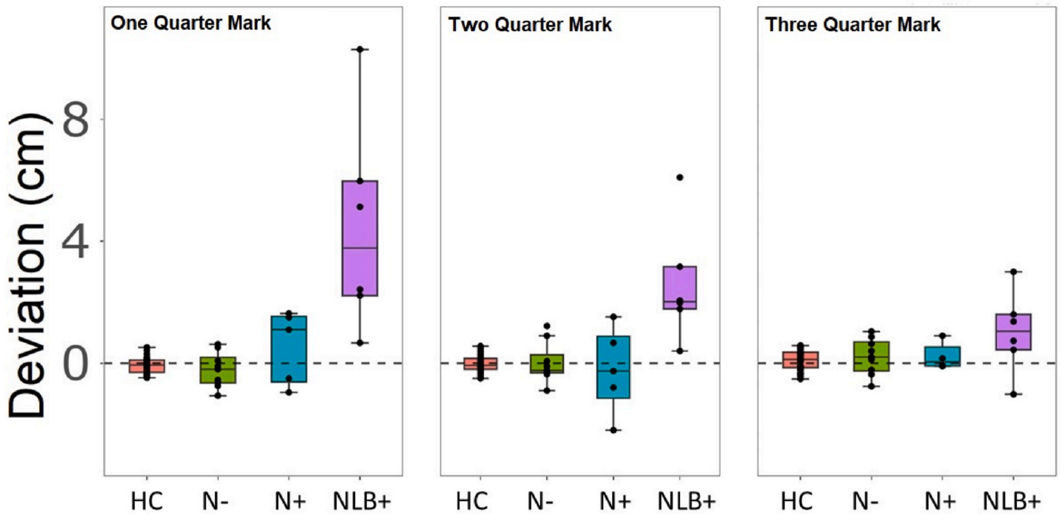

Fig. 2. Quarters task. The x-axis reflects groups; the y-axis denotes the mean deviation from the correct position of the respective mark in cm. Black dots present mean responses of individual participants.

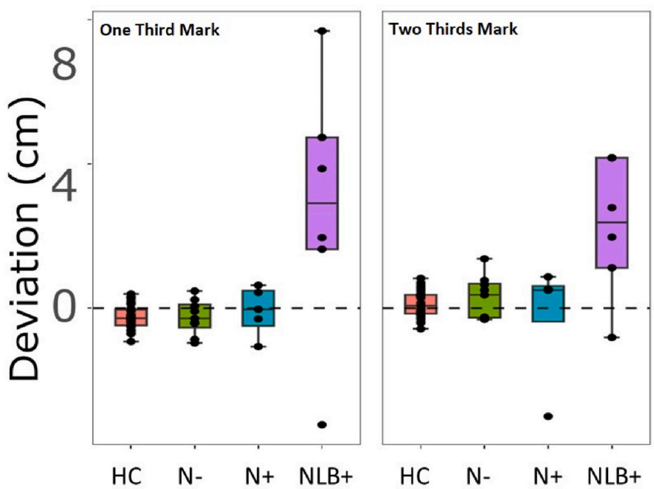

Fig. 3. Thirds task. The x-axis reflects groups; the y-axis denotes the mean deviation from the correct position of the respective marks in cm. Black dots present mean responses of individual participants.

Table 3
Kruskal-Wallis test results for group differences for each line mark in the 'quarters' and 'thirds' subtasks.

Subtask	Position	*H* (df)	*p*
Quarters	1/4	16.54 (3)	<0.001
	1/2	14.80 (3)	0.002
	3/4	5.86 (3)	0.119
Thirds	1/3	7.71 (3)	0.052
	2/3	8.37 (3)	0.039

Table 4
Re-Analysis for each line mark in the 'quarters' and 'thirds' subtask after exclusions.

Subtask	Position	*H* (df)	*P*
Quarters	1/4	11.74 (3)	0.008
	1/2	11.33 (3)	0.010
	3/4	2.00 (3)	0.572
Thirds	1/3	13.33 (3)	0.004
	2/3	8.95 (3)	0.030

significantly differed from all other groups (all adj. $p < 0.05$). For the 2/3 mark, there were no significant group differences after correcting for multiple comparisons. Thus, when patients with 'untypical' responses were excluded, the NLB + group showed responses significantly misplaced towards the right compared to other groups in both the 'quarters' and the 'thirds' subtasks, but only for the leftward marks. Therefore, these results substantiated the results observed with all participants in the *quarters* task, while differing from those including all participants for the *thirds* task. The exclusion of two patients led to significant differences between the NLB + group with all other groups for the 1/3 mark only.

3.3. Fractions

In the *fraction* task, participants had to indicate the spatial location of fractions on a number line ranging from 0 to 1. For this task, two patients had to be excluded from the analyses as they could not complete the task. One was from the NLB + group (P12), and one from the N- group (P15). Participants' responses are displayed in Fig. 4. Statistical details on group comparisons can be found in Table 5. The only indication for a significant difference was found for 2/3. However, no difference between two groups was significant after correction for multiple comparisons.

3.4. Whole numbers

The *whole numbers* task was conceptually identical to *the fractions task*, only that the number line ranged from 0 to 10 instead of 0–1, and participants had to indicate the position of whole numbers. Three patients were not capable of completing the whole number task. Of these, one was the same participant from the NLB + group who could not carry out the *fraction task* (P12), one was from the N- group (P1), and one was from the N+ group (P3). Therefore, they were not considered in the analyses.

Participants' responses are plotted in Fig. 5. Table 6 presents the results of Kruskal-Wallis tests for group comparisons indicating at least one significant group difference for numbers 1, 4, 5, and 9. Post-hoc tests indicated that for number 1, the HC group differed significantly from group N+ (adj. $p = 0.003$). Additionally, there was a marginally significant difference between the HC and NLB + group after correction for multiple comparisons (adj. $p = 0.063$). This indicates that the N+ group placed their marks for the number 1 significantly further to the left compared to the HC group. For number 4, the Kruskal-Wallis test did not

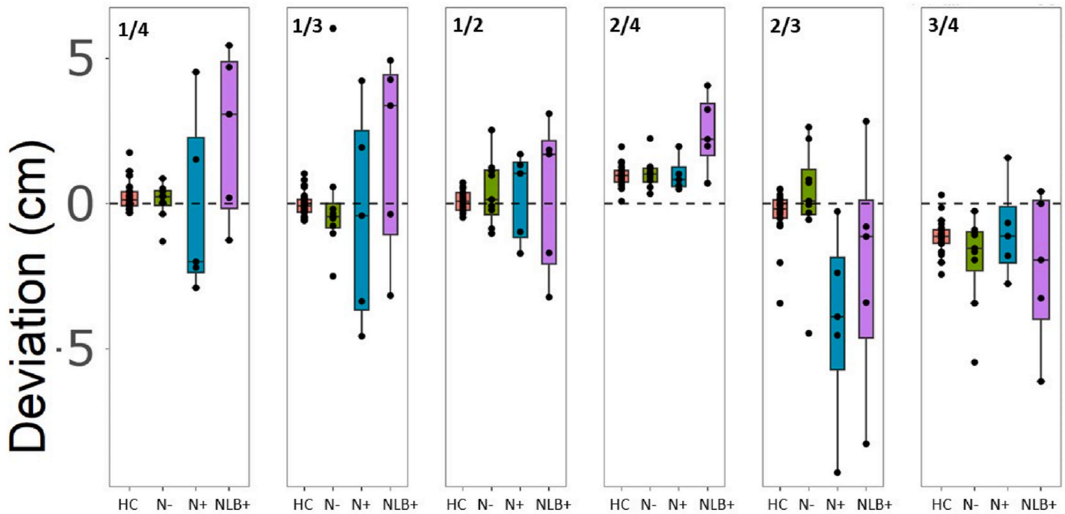

Fig. 4. Fractions task. Individual subplots denote group differences in individual marks (i.e., 1/4, 1/3, 1/2, 2/4, 2/3, 3/4). The x-axis indicates group, and the y-axis reflects the relative deviation in cm from the correct position of the respective mark. Black dots indicate individual participants' mean responses.

Table 5
Kruskal-Wallis test results for group differences for each line mark in the 'fractions' subtask.

Position	*H* (df)	*p*
1/4	3.27 (3)	0.351
1/3	3.45 (3)	0.328
1/2	6.55 (3)	0.088
2/4	1.23 (3)	0.746
2/3	6.26 (3)	0.007
3/4	1.33 (3)	0.722

indicate any significant differences after correcting for multiple comparisons. Therefore, no post-hoc tests were carried out. For number 5, post-hoc tests indicated that the NLB + group differed significantly from all other groups (all adj. p's < 0.05), placing their mark significantly further to the right than the other groups. For number 9, the NLB + group differed significantly from the HC group and marginally significantly (adj. $p = 0.056$) from the N- group. Similarly, the N+ group also differed significantly from the HC and N- groups, whereby participants from the N+ and NLB + group placed their marks further to the right than patients from the HC and N- group.

To summarise, for number 1, the N+ group showed a bias to the left compared to healthy controls, for number 5 the NLB + group showed a bias to the right compared to all other groups, and for number 9 the N+ group showed a bias to the right compared to the HC group and the N- group, while the NLB + group showed a significant bias to the right compared to the HC group only.

Table 6
Kruskal-Wallis test results for group differences for each line mark in the 'whole numbers' task.

Position	*H* (df)	*p*
1	17.44 (3)	<0.001
4	5.20 (3)	0.158
5	11.48 (3)	0.009
6	4.10 (3)	0.251
9	16.77 (3)	<0.001

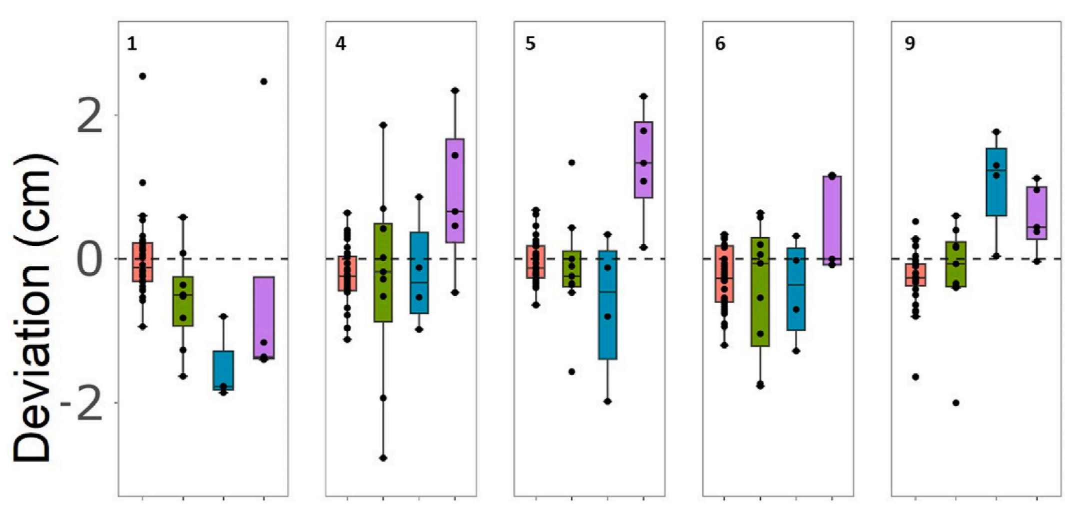

Fig. 5. Whole number task. Individual subplots denote group differences for individual marks (i.e., 1, 4, 5, 6, 9). The x-axis indicates the groups, and the y-axis reflects the relative deviation in cm from the correct position of the respective mark. Black dots indicate individual participants' mean responses.

3.5. Verbal number bisection

Three participants could not carry out the task (P3 [N+], P12 [NLB+], P13 [N-]). All other responses are plotted in Fig. 6. For each participant, the deviation of all responses to the correct number was averaged, and these values were used for group-wise comparisons. As groups N- and NLB + had one outlier each (more than 2 SDs away from the mean), these outliers were excluded from analysis.

A Kruskal-Wallis test was significant for this task ($H(3) = 22.27$, $p < 0.001$), whereby post-hoc Dunn-tests showed that group HC was significantly different from all other groups (all adj. p's < 0.05). All patient groups tended to misbisect towards smaller numbers, i.e. to the "left" of the mental number line.

3.6. Data analysis using a more liberal cut-off value for the diagnostic line bisection task

In addition to the above analyses using a cut-off of 14% to ensure a robust presence of line bisection bias (Ferber and Karnath, 2001), we also performed analyses of our data using a more liberal cut-off of 6.5% (as used in Azouvi et al., 2002) for the diagnostic line bisection task. Under this latter condition, all patients from the N+ group apart from one were included in the NLB + group. Therefore, we had to exclude the N+ group from this second set of analyses. Apart from this, the same exclusions were made as above whenever patients were not able to carry out a task.

Detailed results of these analyses are reported in the supplementary material. In sum, the results lead to the same conclusions as for the more conservative grouping of patients according to a threshold of 14% except for the *whole numbers* task. Here, Kruskal-Wallis tests only indicated differences for numbers 1 and 9. This may in part be explicable due to the increased variance of responses in the merged NLB + group.

4. Discussion

In this study, we evaluated whether line bisection bias in patients with neglect reflects a specific problem in bisecting a line into two equal parts or rather a special case of a deficit in *proportional reasoning* more generally. In the latter case, the bias should also be observed for segmentations into thirds or quarters and potentially number line estimation for which proportion-judgement strategies have been argued. Therefore, patients with neglect presenting or not presenting with a line bisection bias as well as controls had to complete the following tasks in addition to line bisection: i) dissecting a horizontal line into equally sized segments (quarters or thirds), estimating the spatial location of ii) fractions and iii) whole numbers on the line when framed as a number line (ranging from 0 to 1 and 0 to 10, respectively).

Results indicated that in the *segmentations* task, NLB + patients placed leftward marks (i.e., reflecting one quarter, two quarters, and one third) significantly further to the right compared to the other groups. This was not the case for more rightward marks (i.e., 2/3 and 3/4). This suggests that neglect bias indeed generalizes to other segmentations than bisections. Additionally, there was a gradient in their bias decreasing from left to right, which is in line with the notion of different attentional weights of the left and right endpoints influencing performance differentially depending on where on the line the patient was focussing on (see McIntosh et al., 2005). When patients had to orient to more leftward segments of the line, the right endpoint will have exerted a 'stronger attentional pull', thus leading to segmentations being biased more strongly to the right. According to Anderson (1996), this gradient of attentional weighting is likely to be non-linear. This is reflected in the observation that the strength of the segmentation bias depended on the position of the mark to be made (e.g., one quarter vs. three quarters) as well as on the type of segmentation (into quarters or thirds). Based on this we suggest that patients presenting with a line bisection bias may indeed show a more general bias in segmenting and thus proportional reasoning with line bisection only being a special case.

These results are in contrast to Lee et al. (2011), where patients showed larger biases when marking right quarter segments compared to left quarter segments, as well as Gallace et al. (2008), where patients only showed directional biases when they had to divide a line in the middle, but not when dissecting it into smaller parts. These differences are most likely due to methodological differences. For instance, in Lee et al. (2011) patients were explicitly cued to either the left or right region of the line. Moreover, in Gallace et al. (2008) patients were not asked to segment the line, but could reproduce smaller lines (which were given) sequentially on the larger line. Additionally, in the current study, patients with a line bisection bias were examined separately from those without such a bias, as previous research has suggested that line bisection may be performed differently by these groups (e.g., Ferber and Karnath, 2001; Sperber and Karnath, 2016) and has different neural correlates (e.g., Rorden et al., 2006; Verdon et al., 2010; Vossel et al., 2011). This was not the case in Lee et al. (2011) or Gallace et al. (2008).

Nevertheless, the current results fit well with studies comparing ego- and allocentric neglect: For example, in Karnath et al. (2011) patients with neglect were required to visually inspect an image of a house. Patients showed a dynamic gradient in how much of the house they explored depending on whether it was placed more to the left or the right of their egocentric midline. Therefore, in the current segmentation task, a similar effect may have occurred when neglect patients' attention was shifted more to the left or the right of their egocentric midline (in which our tasks were presented), following a gradient of attentional weighting.

Using another two tasks, we also explored whether neglect biases observed for dissecting lines generalized to number line estimations which seems to be based on proportional processing involving dissections of the (number) line given (e.g., Dackermann et al., 2018). In the *fraction* task, we did not observe any specific biases for the neglect patients with a line bisection bias after correction for multiple comparisons. This was most likely due to the large variance in responses in the NLB+ and the N+ groups. Yet, Fig. 4 suggests that the NLB + group showed a similar tendency as in the segmentation task: Smaller, and therefore more leftward fractions (e.g., 1/4) tended to be misplaced more strongly to the right of their correct position on the line. Additionally, larger and thus more rightward fractions were placed too far to the left of their correct position. Taken together, this suggests that participants may have framed the line proportionally when asked to imagine it as a fraction number line.

In the *whole numbers* task, the NLB + group only showed a significant difference to all other groups for number 5 in placing their mark further to the right. For number 1, they showed a non-significant tendency for their mark to be placed to the left of all other groups. For number 9, the N+ group placed their mark significantly to the right of both the healthy controls and the N- group, while the NLB + group placed their mark

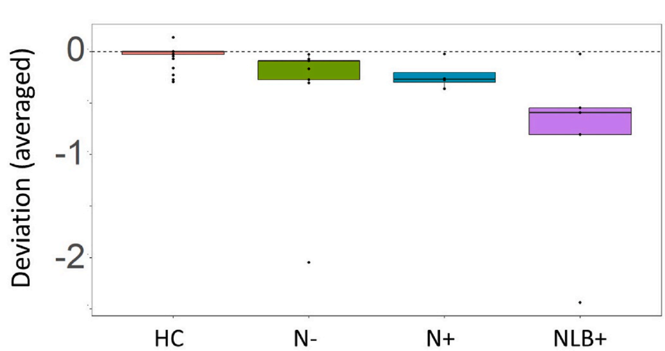

Fig. 6. Verbal number bisection. The x-axis indicates the groups, and the y-axis reflects the relative deviation from the correct number with negative numbers reflecting underestimation of the actual middle number. Black dots show individual participants' mean responses.

significantly to the right of the healthy control group. This suggests that for numbers close to the endpoints, both neglect groups appeared to orient their responses towards these endpoints. When using a more liberal line bisection cut-off (see supplementary materials), the results for the numbers 1 and 9 remained the same, yet the differences for the numbers 4, 5 and 6 vanished.

Generally, these results are in line with evidence from NLE when used to understand the development of magnitude understanding in children (including fractions, e.g., Nuraydin et al., 2023; Siegler and Opfer, 2003). Recent evidence clearly indicates that estimation performance is primarily driven by the use of reference points (i.e., start, end, and midpoint of the number line). Typically, children's estimation become more accurate the more reference points (Dackermann et al., 2018) they consider and thus reflects a clear case of proportional processing. Accordingly, a more general problem with proportional processing instead of a specific one for bisections should lead to the at least descriptively observed pattern of results in patients' number line estimation. However, if exactly the same attentional gradient as in the *segmentations* task were at play, we would have expected the estimation biases of the NLB + group in fraction and whole number line estimation to be more explicit. As such, it seems as if addition of numerical framing to the line segmentation task may have nuanced segmentation biases – potentially due to the introduction of a second structured representation that may allow solving the task (numbers and space vs. space only).

In particular, it is known that in NLE participants estimate the position of numbers close to reference points more accurately as compared to numbers further away from them (e.g., estimating 49 more accurately than 26 on a 0 to 100 number line when using 50 as reference point, Barth and Paladino, 2011). This suggests that participants bias their responses towards the numbers they are most confident in locating. As patients with neglect show difficulties appropriately representing a horizontal line (e.g., Abe and Ishiai, 2022; McIntosh et al., 2005), they may have used a similar strategy: They biased their responses according to the endpoints as well as their perception of where they think number five is located on the line. From there, they placed the numbers four and six accordingly, instead of considering them as proportional marks on the line. This means that the position of marks close to start, end- and midpoint may be chosen differently than numbers further away from these reference points. As such, the number line framing as a conceptual difference to the pure *segmentation* task may have overridden potential segmentation biases. Nevertheless, this observed dissociation is in line with evidence indicating that neglect biases in physical and number space can dissociate and may have differing origins (Doricchi et al., 2005). Importantly, this dissociation was also reflected in the results of the verbal number bisection task. Here, all patients tended to name numbers smaller than those produced by healthy participants, indicating a bias to the left of the mental number line. Yet, these results suggest that patients had difficulties representing numerical proportions correctly. While there were no significant differences between patient groups, the NLB + group showed the descriptively largest bias compared to the other groups. This may indicate that the proportional bias in the numerical domain increases with the proportional bias in the spatial domain, pointing towards a supramodal issue in processing proportions. Yet, the latter conclusion must be interpreted with considerable caution, as indicated by the following section.

4.1. Limitations

When interpreting the results of this study, there are some aspect to consider. First of all, this is the first study evaluating the possibility of a generalized proportion processing deficit in spatial neglect. Accordingly, further studies are necessary to corroborate the conclusions drawn from the current findings. Second, it needs to be acknowledges that the current sample sizes were comparably small. Larger sample size might allow for more insights into expected differences between groups, in particular those hypothesized and observed between neglect patients with and without a line bisection deficit. Additionally, for each task we only used a subset of possible items to keep testing time for patients reasonable. However, more data points might allow for more reliable estimates for each group. For example, in future studies, the whole number task may benefit from participants having to also mark numbers 2, 3, 7, and 8. Furthermore, while the verbal number bisection task indicated that the effect of spatial neglect on proportional reasoning only partly transfers to the domain of verbal numbers, it may be beneficial to also add verbal number segmentation (i.e., a task where thirds or quarters of the number interval are reported) in future studies.

4.2. Conclusion

To conclude, the results of the current study seem twofold. On the one hand, findings from the segmentation task corroborate the idea that line bisection bias in patients with neglect may not reflect a specific problem in bisecting a line into two equal parts. Instead, these data suggest a deficit in *proportional reasoning* more generally as neglect biases generalized to dissecting lines into thirds and quarters. This is corroborated by the observation of a left-to-right gradient in neglect biases with larger rightward biases for segments on the left (i.e., one third, one quarter, two quarters) compared to segments on the right (i.e., two thirds, three quarters). On the other hand, our results also suggest that different framing of the to-be-dissected line as a number line nuanced these biases – potentially due to a focus on reference points for estimating the spatial position of the respective target numbers. Taken together, these results indicate that spatial biases for line bisections in neglect patients seem to be a special case of a more general segmentation/proportional processing bias, which may be influenced by the framing of the respective task.

CRediT authorship contribution statement

S. Smaczny: Writing – review & editing, Writing – original draft, Visualization, Project administration, Investigation, Formal analysis, Data curation. **E. Klein:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **S. Jung:** Writing – review & editing, Methodology, Conceptualization. **K. Moeller:** Writing – review & editing, Methodology, Conceptualization. **H.-O. Karnath:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors have no competing interests to declare.

Data availability

Code and data have been made available online at doi: 10.17632/tbpb2hj3fn.2

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuropsychologia.2024.108848.

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