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Research Report

Weights and measures: A new look at bisection behaviour in neglect

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Abstract

Horizontal line bisection is a ubiquitous task in the investigation of visual neglect. Patients with left neglect typically make rightward errors that increase with line length and for lines at more leftward positions. For short lines, or for lines presented in right space, these errors may 'cross over' to become leftward. We have taken a new approach to these phenomena by employing a different set of dependent and independent variables for their description. Rather than recording bisection error, we record the lateral position of the response within the workspace. We have studied how this varies when the locations of the left and right endpoints are manipulated independently. Across 30 patients with left neglect, we have observed a characteristic asymmetry between the 'weightings' accorded to the two endpoints, such that responses are less affected by changes in the location of the left endpoint than by changes in the location of the right. We show that a simple endpoint weightings analysis accounts readily for the effects of line length and spatial position, including cross-over effects, and leads to an index of neglect that is more sensitive than the standard measure. We argue that this novel approach is more parsimonious than the standard model and yields fresh insights into the nature of neglect impairment.

Theme: Disorders of the nervous system
Topic: Trauma

Keywords: Visual neglect; Line bisection; Cross-over effect

1. Introduction

Horizontal line bisection was first adopted for the diagnosis of visual neglect by Axenfeld [2], who noted in 1915 that patients with right hemisphere lesions often produce large rightward errors. Subsequent commentators have emphasised the inconsistent relationship between such errors and left-sided omissions on other tests diagnostic of neglect, such as drawing [4,18,66] and target cancellation [3,21,26,48,66]. Nonetheless, perhaps due to its ease of administration and quantification, line bisection has assumed a prominent place within the literature, and rightward errors of bisection are considered an important form of neglect behaviour in their own right.

1.1. The standard task description

The standard approach to the bisection task is to describe the stimulus in terms of two independent variables: line length and spatial position (the lateral location of the centre of the line with respect to the body midline). With rare exceptions (e.g. [14,15,42]), the dependent variable is the directional error of bisection relative to the objective midpoint of the line. The effects of line length and spatial position on directional bisection error have been documented extensively.

Several early studies noted that the rightward errors made by neglect patients increase with stimulus length [5,11,57].

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This relationship is well described by a linear function [61], with the slope and intercept of this function varying between patients [23,24,45,46]. Extrapolation of these functions led to the surprising prediction that, in some patients, the bisection error should reverse direction to become leftward for very short lines [23]. This prediction was upheld in a single case [23] and in many more subsequently [25,45,68]. This so-called 'cross-over effect' has now assumed a central importance in constraining models of neglect bisection behaviour.

The spatial position of the stimulus line also affects bisection errors in neglect. In general, the further leftward the line is placed, the more rightward the error [29,57,65]. Interestingly, a cross-over effect analogous to that seen for short lines is associated with the manipulation of spatial position: some patients who produce rightward errors when bisecting lines in left or central hemispace make leftward errors when presented with similar lines in right hemispace [51]. Like the cross-over for short lines, this poses a challenge to models of neglect performance. Any theory that wishes to explain why patients typically make rightward errors must also explain why left neglect is apparently transformed into right neglect under certain conditions.

1.2. Theoretical interpretations of neglect bisection behaviour

An intuitively obvious way to explain rightward errors of bisection is to infer that the patient makes a cognitively normal bisection response but fails to notice a portion of the line at the left. In this account, rightward errors are due to a perceptual 'amputation' of the line [5], which could potentially explain the linear fit between bisection error and line length. However, as Halligan and Marshall pointed out [24], if the attentional boundary occupied a constant peripersonal location for each patient (an assumption adopted to make the theory tractable), the slope of the function relating bisection error to line length should be approximately 0.25. This model was falsified by observing two patients in whom the slope deviated widely from the predicted value, in one case being far too shallow (0.07) and in the other far too steep (0.42) [24].

An alternative proposal is that bisection errors in neglect are due to biases of motor responding [29]. Several methods have been devised to disentangle perceptual and motor contributions to neglect for line bisection and other tasks [6,17,54,58,69]. These studies have suggested that motor biases contribute to bisection errors in at least some patients. However, the tasks employed often depend upon incompatible displacements or reversals of visual feedback from movement and have been criticised on theoretical and practical grounds [31,47]. More recently, it has emerged that there is no consistency of diagnosis across the different methods for the detection of output-related neglect, casting doubt upon the diagnostic category itself [28]. Moreover, no one has yet suggested how motor biases could give rise to the lawful relationships between bisection error and line length that are observed in neglect.

The current dominant theoretical interpretation of bisection errors in neglect can be broadly termed perceptual 'distortion'. Perceptual distortion hypotheses propose that leftward portions of the line, although seen in their entirety, are perceived as laterally compressed relative to rightward extents (e.g. [9,52]). Consistent with this, neglect patients are often biased towards judging the leftward of two line portions [9,27,54] or lateralised shapes [19,33,40,53,55] as being the smaller. Similarly, when required to double the length of a line, neglect patients tend to over-extend in a leftward direction, but to under-extend towards the right [7–9,16,20,64].

Chatterjee and colleagues [14,15] have adopted a psychophysical approach to studying perceptual distortions. They first attempted to map the relationship between objective and subjective line length using power functions [67]. Subjectively represented length was calculated as double the distance between the right hand end of the line and the bisection response [5]. In normal subjects, this was related to the objective length by a power function with an exponent close to one. A group of 16 left neglect patients had a diminished exponent (0.80), suggesting a dampened appreciation of changes in line length, presumably due to underestimation of leftward extents [14]. Chatterjee has recently revised his model by fitting a power function to the relationship between left and right created portions across a range of line lengths [13]. The intention is to map the relationship between subjectively equal extents on the left and right sides and thus to quantify the perceptual distortion in neglect more directly.

Whether linear regressions or power functions are fitted to neglect bisection data, the cross-over for short lines emerges mathematically. However, under current theories, the *explanation* of the cross-over effect requires additional work. If rightward errors are due to a relative underestimation of the left, as perceptual distortion hypotheses imply, then leftward errors presumably reflect its relative *overestimation*. In order to explain both sorts of error within a given patient, Chatterjee and colleagues [1,12] have postulated that neglect involves the impairment of both excitatory and inhibitory attentional processes. The former gives rise to attentional deficits and the underestimation of leftward extents; the latter yields productive symptoms including confabulation of contralesional stimulation. For long lines, the influence of this productive element would tend to be masked, but for short lines, the confabulated leftward extent could exceed the extension on the right side and cause cross-over errors. It is not clear whether this hypothesis can be extended to account for cross-over bisections associated with right hemispatial presentation.

1.3. An alternative view of neglect bisection behaviour

Whilst many researchers have focussed on theoretical and mathematical modelling of bisection errors, Ishiai and colleagues have been investigating the lower-level details of how neglect patients approach the bisection task [34–36,38]. They have found that patients with left neglect tend to look initially somewhere to the right of centre and launch a few exploratory eye movements to the right, but rarely or never look to the left of the line, before placing their transection. It is possible that patients without hemianopia could attend to the left hand end of the line in peripheral vision despite this asymmetrical fixation pattern. However, the patients in Ishiai et al.'s original study had hemianopia and could not have seen any portion of the line to the left of their leftmost fixation [34]. Crucially, their transections were never placed at the centre of the explored portion but were biased to the left of the explored range and were often close to the leftmost fixation. These observations seem incompatible with the notion that the patients were making any normal attempt to bisect the line. The data may undermine the fundamental assumption that neglect patients mark a point that they genuinely perceive to be the middle of the line.

Ishiai et al.'s observations were cited by Kinsbourne [41] in support of a view very different from the conventional one: "In reality, the task of transection as such must be beyond patients with significant neglect, because it requires them to do something of which they are incapable — maintain within conscious visual attention contour on the left as well as on the right of their point of fixation. More likely, patients fixate as far leftward as the severity of their rightward attentional bias permits, and optimistically make their mark at that point" (p.72). Kinsbourne's idea has the unique merit of invoking a single factor to explain both rightward and leftward errors. If a patient is unable to sustain a concurrent awareness of both ends of the line, and thereby judge its length, a rightward or leftward error could result depending on how far left the patient moves before placing their transection (cf. [37]). In this spirit, Koyama et al. have suggested that severe neglect patients strategically transect at a constant distance from the right endpoint of the line [42]. This was based on their observation that, in such patients, the distance between the right endpoint and the transection was relatively stable across large variations in line length and spatial position.

1.4. Recasting the line bisection task

The preceding paragraph highlights a potentially important fact about horizontal line bisection: line length and spatial position may be the standard independent variables, but a horizontal line can be described equally well in terms of the locations of its left and right endpoints. These alternative coding systems are mutually and inextricably confounded. To alter a line's length whilst holding its spatial position constant, or to alter a line's position whilst holding its length constant, implies changes at both endpoints. Koyama et al. [42] entertained the possibility that the left and right endpoints of the line have differential influences on neglect behaviour, but their experiment did not address this issue directly because standard manipulations of line length and spatial position were used. In fact, amongst the hundreds of studies of bisection behaviour in neglect, none has varied the locations of the left and right endpoints independently. However, this is precisely the manipulation required for a fair experimental evaluation of Kinsbourne's account of line bisection [41].

A further consideration for such an experiment is that directional bisection error might not be the most appropriate dependent variable. The use of the error relative to the true midpoint carries the tacit assumption that the response represents the patient's subjective midpoint and thereby conveys information about the patient's spatial perception. As just noted, however, this may not be a safe assumption to make. The most assumption-free approach would be to treat the transection simply as a spatial response. Rather than coding its location relative to any part of the stimulus, we would code its location with respect to some fixed point in the testing environment, such as the body midline.

In summary, an empirical evaluation of Kinsbourne's account of line bisection [41] requires us to avoid certain conventional assumptions and to select new independent and dependent variables. In the bisection experiments to be reported, the independent variables will be the egocentric lateral locations of the left and right endpoints of the stimulus line (*L* and *R* respectively). The dependent variable will be the egocentric lateral position of the patient's response (P). The aim of the first experiment will be to explore, in the simplest manner, how P changes when *L* and *R* are manipulated independently.

2. Methods

2.1. Subjects

Thirty patients (18 female, 12 male) with left visual neglect following unilateral right hemisphere stroke participated in this study. Unilateral brain damage was determined from clinical signs and/or clinical brain imaging (Computerised Tomography or Magnetic Resonance). Visual neglect was assessed using four conventional sub-tests of the Behavioural Inattention Test [70] and a scene copying task adapted from Gainotti et al. [22]. In order to survey patients across the full range of neglect severity, a liberal inclusion criterion, the presence of left neglect on one or more of these diagnostic tasks, was applied. Details are given in Table 1. All patients were right-handed by self-report, except for patients VN22 and VN27 who were left-handed.

All patients took part in Experiment 1, which was performed following the initial screening (median interval 2 days; range 0–41). Thirty healthy control subjects (18 female, 12 male), with no history of neurological illness, also took part in Experiment 1. All control subjects were right-handed by self-report, except for two who were left-handed. The mean age of the healthy control (HC) group (71.27 years; SD 9.12) did not differ significantly from that

Table 1
Clinical details of visual neglect (VN) patients

VN patient	Age/sex	Lesion site	Post-stroke	VFD (+/−)	Lines *L*/*R*	Stars *L*/*R*	Copy (sym/it)	Draw (0–3)	Bisect (0–9)
VN01	77/F	FTPS	56	−	**0/39**	**0/15**	**0/1**	**1**	**0**
VN02	63/M	F	16	−	**67/100**	**37/89**	**0/2**	**2**	**5**
VN03	67/M	FTPS	15	−	94/100	**59/96**	**4/5**	3	**4**
VN04	77/F	FP	5	−	100/100	**59/85**	5/5	**2**	5
VN05	81/M	FS	4	−	100/100	**74/96**	**4/5**	3	4
VN06	61/M	FPO	0	+	**0/50**	**0/37**	**0/1**	**0**	**0**
VN07	74/F	na	1	+	**67/100**	**19/52**	**0/2**	**1**	**0**
VN08	64/M	FTP	15	+	**28/89**	**0/41**	**1/2**	**0**	**2**
VN09	82/F	na	2	+	100/100	93/100	5/5	3	**0**
VN10	81/F	FTP	6	+	**0/33**	**0/30**	**0/2**	**0**	**0**
VN11	51/M	FTPOS	9	+	**56/100**	**11/74**	**0/2**	3	9
VN12	75/M	FT	5	−	100/100	**0/44**	**1/2**	**0**	**3**
VN13	63/F	FTP	20	+	**0/100**	**0/52**	**2/2**	3	**3**
VN14	80/M	TO	7	+	**33/89**	**56/96**	5/5	3	**5**
VN15	62/F	FTPS	7	−	**89/100**	67/74	**3/4**	**2**	**5**
VN16	67/M	TP	5	−	**89/100**	**81/100**	5/5	**2**	**5**
VN17	53/F	FT	2	−	**0/61**	**0/37**	**1/5**	**1**	**0**
VN18	67/F	FP	13	−	**39/94**	**0/63**	**1/2**	**2**	3
VN19	47/F	TPOS	9	+	94/100	**48/100**	5/5	**2**	8
VN20	72/M	P	11	−	100/100	96/93	5/5	3	**7**
VN21	52/F	FTP	6	+	94/100	**78/93**	**4/4**	3	**1**
VN22	79/F	na	7	+	94/100	**67/96**	na	na	**6**
VN23	70/F	FT	4	−	94/100	100/100	**3/5**	3	**3**
VN24	74/F	TS	7	−	100/100	100/96	5/5	**1**	5
VN25	73/F	F	2	−	100/100	**37/74**	**0/2**	**0**	**5**
VN26	76/F	TP	4	−	100/100	89/85	5/5	**2**	**6**
VN27	75/F	na	16	−	100/100	89/96	**4/5**	**2**	8
VN28	73/M	P	1	+	100/100	100/96	5/5	3	**6**
VN29	76/M	FTS	9	−	100/100	**89/100**	5/5	3	**2**
VN30	75/F	F	3	+	**89/100**	**67/93**	5/5	**1**	**4**

Lesion site determined from clinical brain imaging: F, frontal; T, temporal; P, parietal; S, subcortical; na, not available. Time post-stroke is given in weeks. VFD, visual field defect to confrontation. Lines (*L*/*R*), percentage omissions in each half of line crossing sheet. Stars (*L*/*R*), percentage omissions in each half of star cancellation sheet. Copy (sym/it), number of items copied symmetrically/number of items attempted (from 5). Draw (0–3), number of drawings symmetrically copied. Bisect (0–9), score on line bisection test (see [70]). Bold values indicate presence of left neglect.

of the visual neglect (VN) group (69.57 years; SD 9.59) [$t(58) = 0.70$, P = 0.49].

Twelve patients (VN1–VN12) additionally took part in Experiments 2 and 3. Experiment 2 was performed following Experiment 1 (median interval 1.5 days; range 0–26) and Experiment 3 following Experiment 2 (median interval 1 days; range 0–5).

2.2. Experiment 1

Bisection stimuli, 3 mm thick, were printed individually in black ink on white A4 paper in landscape orientation. Two types of stimuli were used: horizontal lines and horizontal gaps. The gaps were identical to the lines except that only the terminal 4 mm of the line at either end was printed. For each stimulus type, four stimuli were created by the factorial combination of two locations of the left endpoint ($L = -40$ and -80 mm with respect to the page midline) with two locations of the right endpoint ($R = +40$ and $+80$ mm with respect to the page midline). The dependent measure was the response position (P), coded with respect to the page midline. Each patient completed four blocks of 16 trials (four for each stimulus) with stimulus type blocked in an ABBA schedule, beginning with lines. Stimuli within each block were presented in a fixed pseudo-random order or its reverse, according to an ABAB schedule. On each trial, the sheet was placed directly in front of the patient, with the page midline aligned with the body midline. Patients were required to mark the midpoint of the line or gap stimulus with a pen held in the right hand. Patients were required to remove their hand from the table after each response to prevent them adopting an invariant response position. All patients completed Experiment 1 in a single session, with a break after each block if required. Since no overall effect of stimulus type (line, gap) was observed amongst the patients (see Analysis), control subjects were tested using the line stimuli only, with all other aspects of the procedure remaining identical.

2.3. Experiment 2

In this experiment, line stimuli only were presented. Nine stimuli were created by the factorial combination of three left endpoint locations ($L = -10$, -30 and -50 mm) with three right endpoint locations ($R = +10$, $+30$ and $+50$ mm). Each subject completed two blocks of 36 trials (four for each stimulus). Stimuli in the first block were presented in a fixed pseudo-random order, which was reversed in the second block. The procedure was otherwise identical to that used in Experiment 1.

2.4. Experiment 3

In this experiment, a set of ten stimulus lines was used, depicted in Fig. 5 (see Results). In terms of the standard description of the line bisection task, lines A–F in Fig. 5 occupy the same spatial position since their midpoints are aligned but vary in length. Lines G–J together with D make a set of lines of identical length that vary in spatial position. Each subject completed two blocks of 40 trials (four for each stimulus). Stimuli in the first block were presented in a fixed pseudo-random order, which was reversed in the second block. The procedure was otherwise identical to that used in Experiment 1.

2.5. Analysis

It must be emphasised that the dependent variable P codes the lateral position of each response with respect to the page midline, which was always presented in correspondence with the subject's body midline. This measure is importantly different from the standard measure of directional bisection error, which records the bisection response with respect to the objective centre of the line. It is nonetheless worth noting that, because the left and right endpoint locations were, on average, symmetrical around the page midline, the mean value of P in each experiment is equivalent to the mean directional bisection error.

For Experiment 1, an initial ANOVA was conducted for the VN group alone, with stimulus type (line, gap), left endpoint location (−40, −80 mm) and right endpoint location (+40, +80 mm) as within-subject factors. Neither the main effect of stimulus type nor any interaction involving this factor approached significance. This was unexpected, in light of previous findings that rightward bisection errors amongst neglect patients are typically reduced when gap stimuli rather than line stimuli are presented [8,49]. However, given this null finding and the fact that Experiments 2 and 3 employed line stimuli only, further testing and analysis was restricted to line stimuli. The HC group in Experiment 1 was accordingly tested with line stimuli only, and all further analyses will refer exclusively to line stimuli.

3. Results

3.1. Experiment 1

3.1.1. Group analyses

The mean responses of the HC and VN groups to each of the four stimulus lines are shown in Fig. 1a. Heterogeneity of variance between groups precluded their statistical comparison by ANOVA. However, an independent t test, with degrees of freedom corrected for unequal variances, confirmed that the VN group responded further rightward overall than the HC group [$t(30.05) = 3.29$, $P = 0.003$]. One-sample t tests for each group found that the mean HC response (−0.54 mm, SD 1.84) did not differ significantly from zero [$t(29) = 1.60$, $P = 0.12$], whilst the mean VN response (7.77 mm, SD 13.70) was biased significantly rightward [$t(29) = 3.11$, $P = 0.004$].

In order to explore the influence of left endpoint location ($L = -40, -80$ mm) and right endpoint location ($R = +40, +80$ mm) on response position (P), separate repeated-measures ANOVAs were conducted for each group. For the HC group, significant effects of both L [$F(1,29) = 10{,}698.80$, $P < 0.0001$] and R [$F(1,29) = 4692.87$, $P < 0.0001$] were found, with no interaction [$F(1,29) = 0.002$, $P = 0.96$]. Similarly, for the VN group, L [$F(1,29) = 108.53$, $P < 0.0001$] and R [$F(1,29) = 406.74$, $P < 0.0001$] had significant

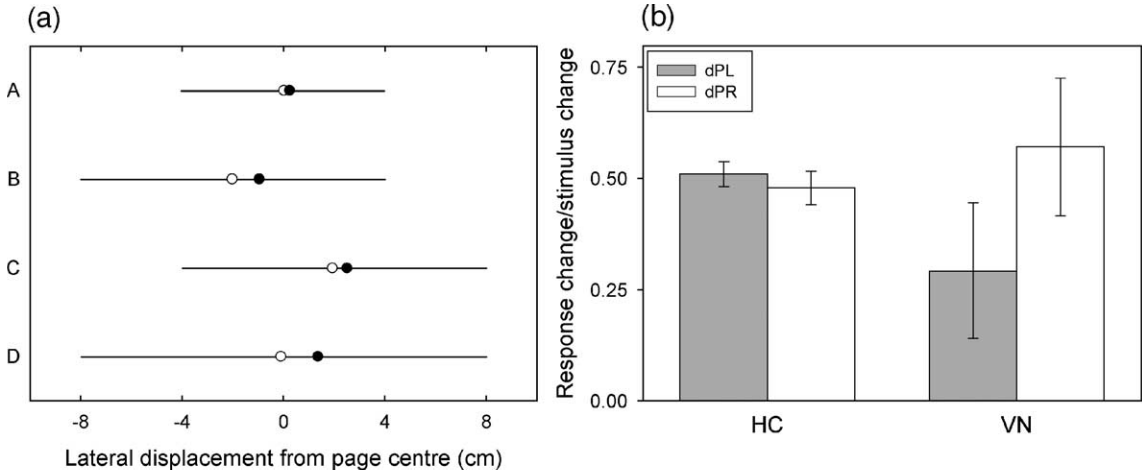

Fig. 1. Experiment 1. (a) Mean P for HC group (open circles) and VN group (filled circles) for each stimulus line (A–D). (b) Mean left endpoint weighting (dP_L) and right endpoint weighting (dP_R) ± SD for HC and VN groups.

influences, but their interaction was not significant [$F(1,29) = 0.72$, $P = 0.40$].

In Fig. 1b, the group data have been replotted to show the mean change in P associated with a shift in either endpoint between its two locations, expressed as a proportion of the size of the stimulus change (40 mm). These values (dP_L and dP_R) are equivalent to the slope of the linear relationship between endpoint location and response position and can be considered to reflect the 'weightings' that the left and right endpoints respectively have in determining the response. In the present experiment, left and right endpoint weightings can be calculated from the following equations (see Fig. 1a):

$$dP_L = (\text{Mean P in conditions A and C}) - (\text{Mean P in conditions B and D}) \quad (1)$$

$$dP_R = (\text{Mean P in conditions C and D}) - (\text{Mean P in conditions A and B}) \quad (2)$$

Fig. 1b shows that, relative to HC subjects, VN patients had a reduced weighting for the left endpoint and an increased weighting for the right; both of these differences were found to be significant using independent t tests corrected for unequal variances [$t(30.84) = 7.64$, $P < 0.0001$; $t(32.38) = 3.13$, $P = 0.004$ respectively]. Additionally, paired t tests were used to compare dP_L and dP_R within each group. Amongst HC subjects, dP_L was significantly higher than dP_R [$t(29) = 3.93$, $P = 0.002$], whilst the reverse was true in the VN group [$t(29) = 5.27$, $P < 0.0001$]. That is, control subjects showed a reliably higher weighting for the left endpoint than for the right, and this pattern was reversed, and much exaggerated, amongst neglect patients.

3.1.2. Individual analyses

As a group, the bisection responses of VN patients were less affected by a change in the location of the left endpoint of the line than by a comparable change at the right hand end. In order to examine variations in this tendency at an individual level, separate factorial ANOVAs were conducted for each patient, with L (−40, −80 mm) and R (+40, +80 mm) as factors. Table 2 presents the outcome of these ANOVAs, in terms of effect sizes (partial eta squared: η_p^2) and significance levels, with associated dP_L and dP_R scores.

Table 2
Analyses for individual patients in Experiment 1

VN patient	Bisection error (mm)	Endpoint weightings		Effect size (η_p^2) at ANOVA		
		dP_L	dP_R	L	R	L* R
VN1	10.13	0.08	0.67	0.04	0.76**	0.05
VN2	0.29	0.29	0.39	0.75**	0.85**	0.09
VN3	6.09	0.42	0.54	0.88**	0.92**	0.07
VN4	−2.97	0.38	0.55	0.76**	0.87**	0.03
VN5	−4.06	0.50	0.42	0.88**	0.84**	0.00
VN6	38.91	0.01	0.90	0.00	0.90**	0.03
VN7	8.11	0.33	0.65	0.51**	0.80**	0.02
VN8	10.16	0.31	0.60	0.74**	0.91**	0.02
VN9	50.41	0.02	0.88	0.01	0.93**	0.06
VN10	44.59	0.05	0.95	0.03	0.92**	0.09
VN11	4.81	0.25	0.58	0.46**	0.82**	0.07
VN12	9.44	0.34	0.56	0.82**	0.92**	0.00
VN13	2.34	0.20	0.57	0.22*	0.70**	0.01
VN14	5.13	0.20	0.56	0.08	0.43**	0.01
VN15	−1.69	0.39	0.45	0.86**	0.89**	0.04
VN16	1.09	0.43	0.44	0.91**	0.92**	0.01
VN17	11.63	0.15	0.68	0.10	0.70**	0.01
VN18	2.56	0.38	0.45	0.67**	0.74**	0.05
VN19	−0.53	0.27	0.56	0.53**	0.83**	0.01
VN20	0.91	0.39	0.49	0.83**	0.86**	0.06
VN21	21.91	−0.01	0.84	0.00	0.85**	0.02
VN22	2.34	0.50	0.41	0.85**	0.79**	0.01
VN23	−0.72	0.55	0.58	0.97**	0.97**	0.06
VN24	−4.34	0.28	0.37	0.55**	0.68**	0.02
VN25	−1.47	0.38	0.35	0.87**	0.84**	0.02
VN26	4.44	0.44	0.55	0.96**	0.97**	0.10
VN27	2.5	0.19	0.56	0.42**	0.86**	0.02
VN28	4.25	0.30	0.46	0.57**	0.76**	0.01
VN29	6.09	0.36	0.64	0.92**	0.97**	0.07
VN30	0.78	0.42	0.49	0.59**	0.66**	0.02
MEAN (SD)	7.77 (13.70)	0.29 (0.15)	0.57 (0.16)	0.56 (0.34)	0.83 (0.12)	0.04 (0.03)

* Significant at $P < 0.05$.
** Significant at $P < 0.0005$.

These analyses showed that, in terms of endpoint weightings and effect sizes, the vast majority of VN patients were more influenced by the right than by the left endpoint of the line. However, there was considerable individual variation in this tendency. In some patients, the predominance of the right endpoint was marginal, and, in two patients (VN4, VN22), the left endpoint clearly had the greater influence. At the other extreme were seven patients in whom the left endpoint had no reliable influence upon the mean response (VN1, VN6, VN9, VN10, VN14, VN17 and VN21). In no patient did the influence of the two endpoints interact, suggesting that the endpoint weightings are independent of the distance between the endpoints (thus independent of line length).

To illustrate the range of individual performances more vividly, Fig. 2 shows the mean responses for patients VN1–VN12, providing a representative sample across the spectrum of neglect severity. In four of these patients, the left endpoint had no reliable influence on P (VN1, VN6, VN9, VN10). In all other patients shown, with the exception of VN5, the influence of the left endpoint was reliable but reduced relative to that of the right. Fig. 2 additionally illustrates that, in terms of bisection error (relative to the true midpoint of the line), most patients responded as expected, tending further rightward for longer lines (compare lines A and D) and for lines in a more leftward spatial position (compare lines B and C). These familiar regularities underline the fact that the endpoint weightings analysis simply provides an alternative description of classical neglect bisection behaviour—the phenomena under study remain unchanged.

3.1.3. Relationship between endpoint weightings

Fig. 3a shows a scatterplot relating the left and right endpoint weightings for the 30 patients and their matched controls. Ideal performance is represented by the intersection of dotted lines at symmetrical endpoint weightings of 0.5. The control subjects cluster loosely around this point. By contrast, the neglect patients almost all had a low weighting for the left endpoint ($dP_L < 0.5$) and a higher weighting for the right endpoint. There was a significant inverse relationship between the left and right endpoint weightings amongst the neglect group (Spearman's $\rho = -0.64$, $P < 0.0005$), evocative of the many laterally competitive interactions that characterise the syndrome (e.g. [41]).

3.1.4. Endpoint weightings bias

The inverse relationship between endpoint weightings suggests that one simple measure of neglect impairment on this task is the difference between the endpoint weightings, which shall be referred to as the 'endpoint weightings bias' (EWB = $dP_R - dP_L$). The ideal value of EWB is zero; positive values reflect a greater influence of the right endpoint, and negative values a greater influence of the left. Fig. 3b shows that EWB is strongly related to the conventional directional bisection error within the VN group (Spearman's $\rho = 0.77$, $P < 0.0005$), suggesting that these two indices measure substantially the same bias. However,

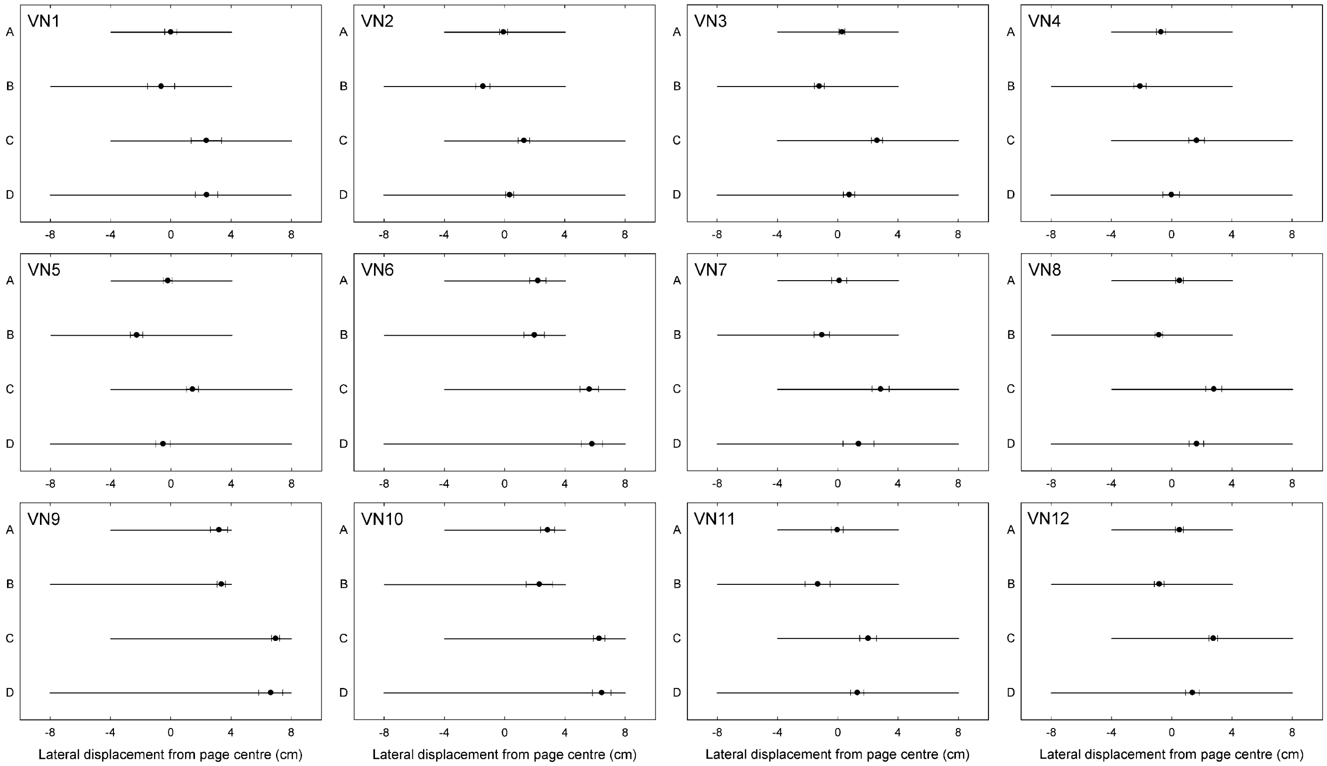

Fig. 2. Experiment 1. Individual data for patients VN1–VN12, showing mean P ± SD for each stimulus line (A–D).

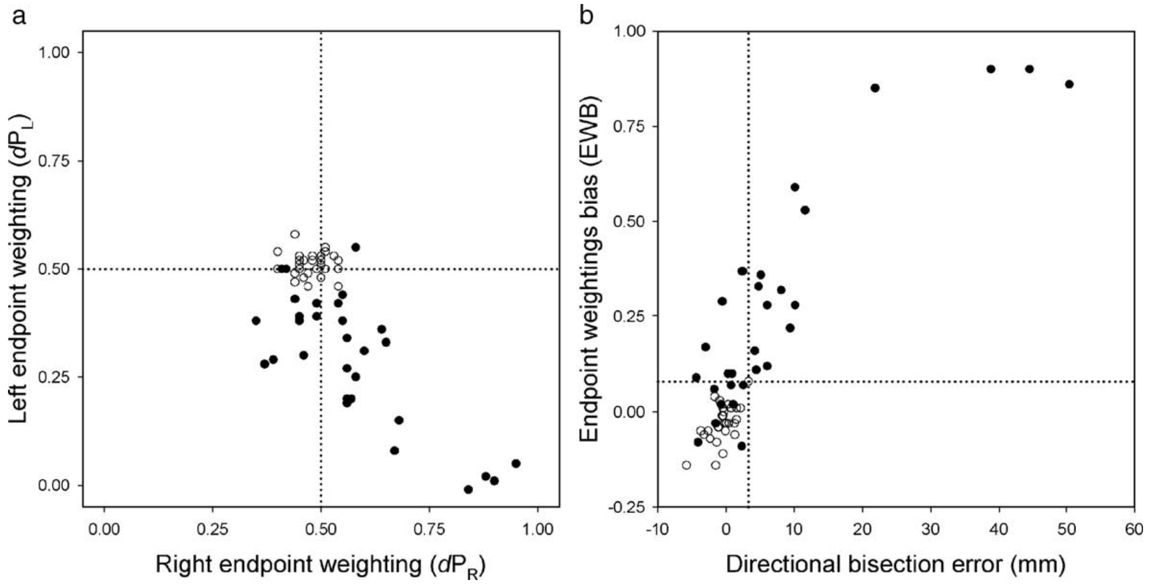

Fig. 3. Experiment 1. (a) Scatterplot relating right and left endpoint weightings for HC subjects (open circles) and VN patients (filled circles). The intersection of the dotted lines at symmetrical endpoint weightings of 0.50 represents ideal performance. (b) Scatterplot relating directional bisection error and endpoint weightings bias for HC subjects (open circles) and VN patients (filled circles). The dotted lines represent cut-offs for left neglect on each axis, as defined by the highest HC score on that index.

there is a cleaner separation between the neglect and healthy groups in terms of EWB than in terms of bisection error, which suggests that EWB may be the more sensitive measure. The dotted lines in Fig. 3b represent the cut-off for left neglect on each axis, as determined by the maximum value achieved by any healthy subject. Fifteen patients scored above cut-off for directional bisection error, whilst 22 had an abnormally high EWB. Accordingly, seven patients were identified with left neglect by EWB that were not identified by directional bisection error (upper left portion of Fig. 3b). By contrast, no patient was identified with left neglect by directional bisection error that was not also identified by EWB (lower right portion of Fig. 3b).

In this regard, it is also worth considering directional bias amongst healthy subjects. It is generally acknowledged that neurologically normal populations exhibit an average leftward bias on line bisection, which is sometimes termed ‘pseudoneglect’ (after [10]). However, this bias is small, subject to considerable individual variation and often fails to reach significance in group studies (see [39] for a review and meta-analysis). As reported in the group analyses above, the mean bisection error of the HC group was leftward (−0.54 mm, SD 1.84), but non-significantly so [one sample $t(29) = 1.60$, $P = 0.12$]. However, if EWB is considered, the leftward mean bias (−0.03, SD 0.05) becomes highly significant [one sample $t(29) = -3.36$, $P = 0.002$]. This supports the view that EWB is a highly sensitive measure of directional bias on this task.

3.1.5. Summary of Experiment 1 results

Experiment 1 shows that the locations of the left and right endpoints of a bisection stimulus can be considered as having independent influences upon the response. The lack of interaction between these influences suggests that the endpoint weightings capture some underlying stimulus-invariant feature of performance. It further appears that EWB, the asymmetry in the endpoint weightings, is an especially sensitive measure of directional bias. Left neglect is characterised by an abnormally positive EWB, which reflects a dominant influence of the right endpoint. The results further indicate that, in certain patients, the location of the left endpoint has no influence at all upon the mean response. However, it is possible that this apparent absence of influence of the left endpoint may have been due to the use of reasonably long stimulus lines (80–160 mm), so that patients may have failed to explore the line fully to the left. Experiment 2 was therefore designed to test whether the findings of Experiment 1 would hold for shorter bisection stimuli.

3.2. Experiment 2

The range of line lengths presented in Experiment 2 (20–100 mm) was selected in order to overlap with that presented in Experiment 1 (80–160 mm), whilst also including some very short lines. At a viewing distance of 40 cm, the shortest line would subtend less than 3° of visual angle, so it is unlikely that exploratory deficits would prevent patients, even those with hemianopia, from viewing these lines in their entirety. Therefore, if a failure to be influenced by the left endpoint were due simply to a failure to see it, then this might occur for the longer lines in the set but should not occur for the shortest.

The performances of the 12 VN patients tested are detailed in Table 3. Overall, the severity of neglect exhibited was lower than in Experiment 1, both in terms of mean

Table 3
Analyses for individual patients in Experiment 2

VN patient	Bisection error (mm)	Endpoint weightings		Effect size (η_p^2) at ANOVA		
		dP_L	dP_R	L	R	L^*R
VN1	2.68	0.28	0.66	0.69**	0.92**	0.08
VN2	−1.87	0.48	0.44	0.96**	0.95**	0.04
VN3	1.9	0.40	0.56	0.97**	0.98**	0.08
VN4	−3.46	0.47	0.48	0.92**	0.93**	0.12
VN5	−5.63	0.54	0.34	0.83**	0.66**	0.09
VN6	6.82	0.06	0.82	0.07	0.89**	0.06
VN7	2.41	0.36	0.56	0.70**	0.85**	0.03
VN8	3.26	0.38	0.66	0.86**	0.95**	0.08
VN9	21.29	0.00	0.92	0.00	0.98**	0.03
VN10	17.6	−0.02	0.93	0.01	0.95**	0.09
VN11	1.19	0.33	0.64	0.71**	0.90**	0.28**
VN12	2.53	0.42	0.52	0.95**	0.97**	0.09
MEAN (SD)	4.06 (7.94)	0.31 (0.19)	0.63 (0.19)	0.64 (0.38)	0.91 (0.09)	0.09 (0.07)

* Significant at $P < 0.05$.
** Significant at $P < 0.0005$.

bisection error (even if considered as a percentage of mean line half-length) and in terms of the asymmetry of endpoint weightings (the difference was most marked in patient VN1). This reduction in neglect severity may be due to a practice effect and/or to improvement of neglect between testing sessions. However, the *pattern* of performance was very similar to that observed in Experiment 1, with ten patients showing a higher weighting for the right endpoint than the left and no significant influence of the left endpoint in three cases (VN6, VN9, VN10). With the exception of VN11, no patient showed a significant interaction between left and right endpoint locations, implying that the weighting accorded to each endpoint is relatively constant across a wide range of line lengths, including short lines. Accordingly, the lack of influence of the left endpoint cannot be ascribed simply to a failure to view the left end of the line.

Fig. 4 displays the mean responses for each of the nine stimulus lines for each of the 12 participating patients, who were also shown in Fig. 2. The performance of patient VN6 is especially illuminating. As in Experiment 1 (Fig. 2), the responses of this patient were insensitive to the left endpoint of the line, whilst slavishly tracking the right. Fig. 4 illustrates that this behaviour produces increasingly rightward responses, with respect to the midpoint of the line, with increasing line length at a given spatial location (compare lines A, E and I). It also results in a cross-over effect, such that responses are made abnormally leftwards with respect to the centre of the line for short stimuli. As can be inferred from the standard deviation of the mean response, patient VN6 sometimes placed his transection mark on the empty page beyond the left hand end of the shortest line. Remarkable as this behaviour seems, it has been reported previously [23,68], and Fig. 4 shows that it fits naturally into the overall pattern of this patient's responding. The fact that patient VN6 could mark the page to the left of the entire line strongly suggests that he must have been able to view the whole of the line. Accordingly, his failure to take account of the left endpoint, even for such short stimuli, must have some explanation other than a simple exploratory deficit.

Experiment 2 strongly reinforces the conclusion from Experiment 1 that the two line endpoints may have independent influences on bisection responses. By testing patients over a greater range of stimuli, Experiment 2 shows even more clearly that a reduced weighting for the left endpoint is consistent with increases of directional bisection error with increasing line length. This effect is apparent, to a greater or lesser degree, for all patients shown in Fig. 4. Similarly, classical spatial position effects are also obtained, with errors becoming more rightward for lines in further leftward locations (compare lines C, E and G). The strength of the spatial position and line length effects vary between patients and are not related to one another in any obvious manner. Nonetheless, both emerge naturally from each patient's combination of left and right endpoint weightings. We tested this impression across a more varied selection of stimulus lines in Experiment 3.

3.3. Experiment 3

Experiment 3 was conducted to explore more extensively the compatibility of the endpoint weightings analysis with the classically observed effects of line length and spatial position. In contrast to Experiments 1 and 2, left and right endpoint locations were not manipulated orthogonally. Instead, eight mirror-image endpoint locations on the left and right were combined to produce a set of stimuli containing a simple manipulation of line length and a simple manipulation of spatial position. As shown in Fig. 5, stimuli A–F were all centred on the page, differing only in length (20, 40, 80, 120, 160 and 240 mm respectively), whilst stimuli G, H, D, I and J were all 120 mm long but centred at different lateral positions on the page (−60, −20, 0, 20, 60 mm respectively).

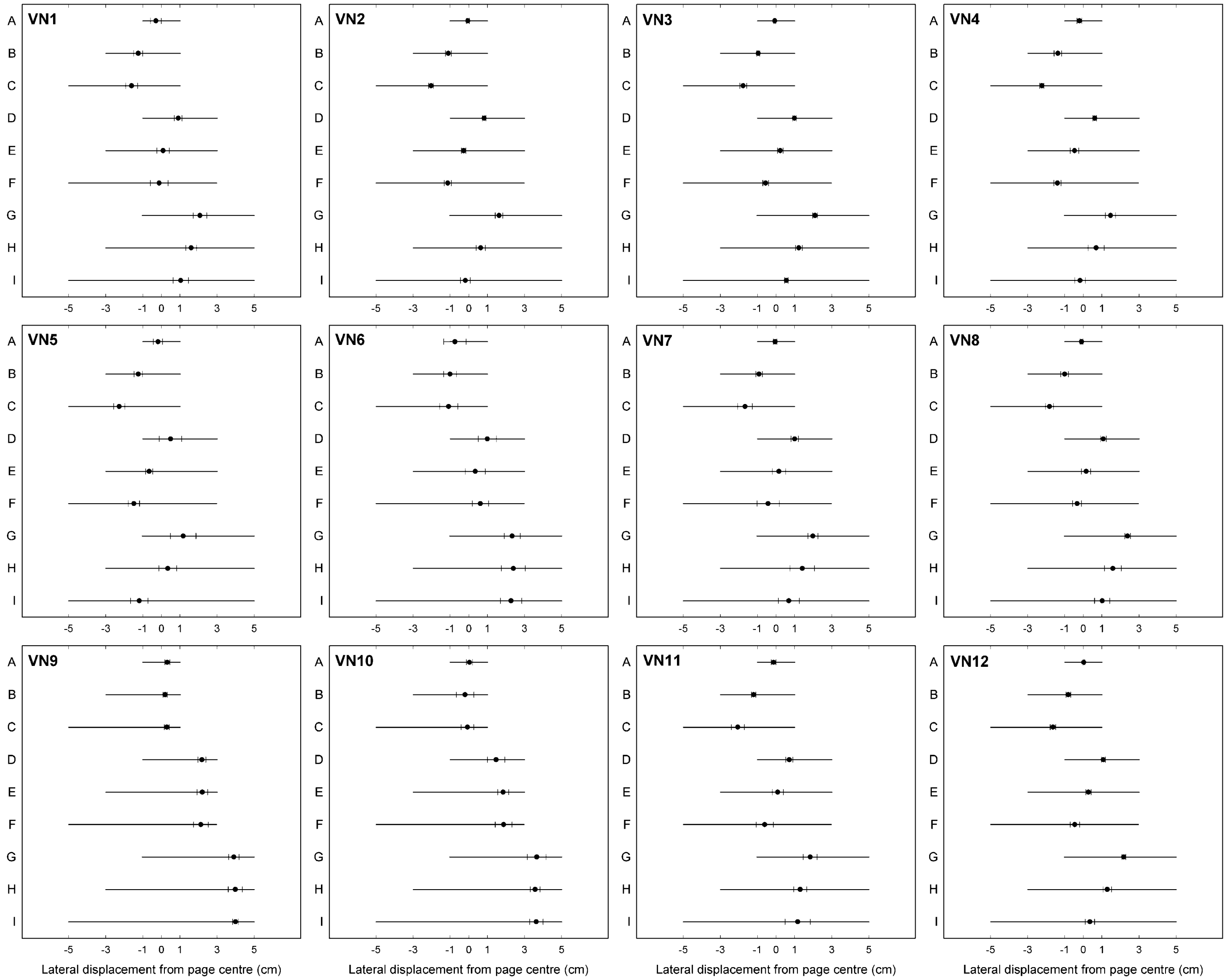

Fig. 4. Experiment 2. Individual data for patients VN1–VN12, showing mean P ± SD for each stimulus line (A–I).

Fig. 5 shows the mean responses produced by each of the 12 participating VN patients. Errors generally became more rightward with increasing line length and, in some patients, crossed over to become leftward for short stimulus lines (e.g. patients VN1, VN6, VN11). Similarly, errors became more rightward with increasingly leftward line placement and, in some patients, crossed over to become leftward for lines presented in right hemispace (e.g. patients VN1, VN2, VN4, VN11). Patient VN5 alone showed a reversal of the line length effect normally seen in neglect patients, producing further leftward errors with increasing line length. Interestingly, despite the reversal of the normal line length effect, this patient showed a spatial position effect of the kind normally observed in left neglect, with errors becoming increasingly leftward for lines presented at further rightward locations.

Each patient's data were subjected to an endpoint weightings analysis in which the mean values of P for each condition were regressed upon the left and right endpoint locations according to a linear model. The slope of the relationship between each endpoint and P gives the weighting for that endpoint. The values of dP_L and dP_R thus derived are shown for each subject in Table 4, along with the regression constant k and the proportion of the variance accounted for by the regression equation:

$$\mathrm{P} = (dP_L L) + (dP_R R) + k \tag{3}$$

The accuracy of prediction was near perfect in every case. However, it should be noted that the above regression is concerned with predicting P (the lateral position of the response in peripersonal space), whereas directional bisection error is more usually the dependent variable of interest for models of bisection behaviour. Eq. (3) can be modified to predict bisection error (B) simply by subtracting the peripersonal location of the line midpoint, given by $(L + R)/2$, from the term for response position P:

$$B = [(dP_L L) + (dP_R R) + k] - [(L + R)/2] \tag{4}$$

Fig. 6 shows a scatterplot relating predicted and observed B for each patient; the proportion of the variance accounted

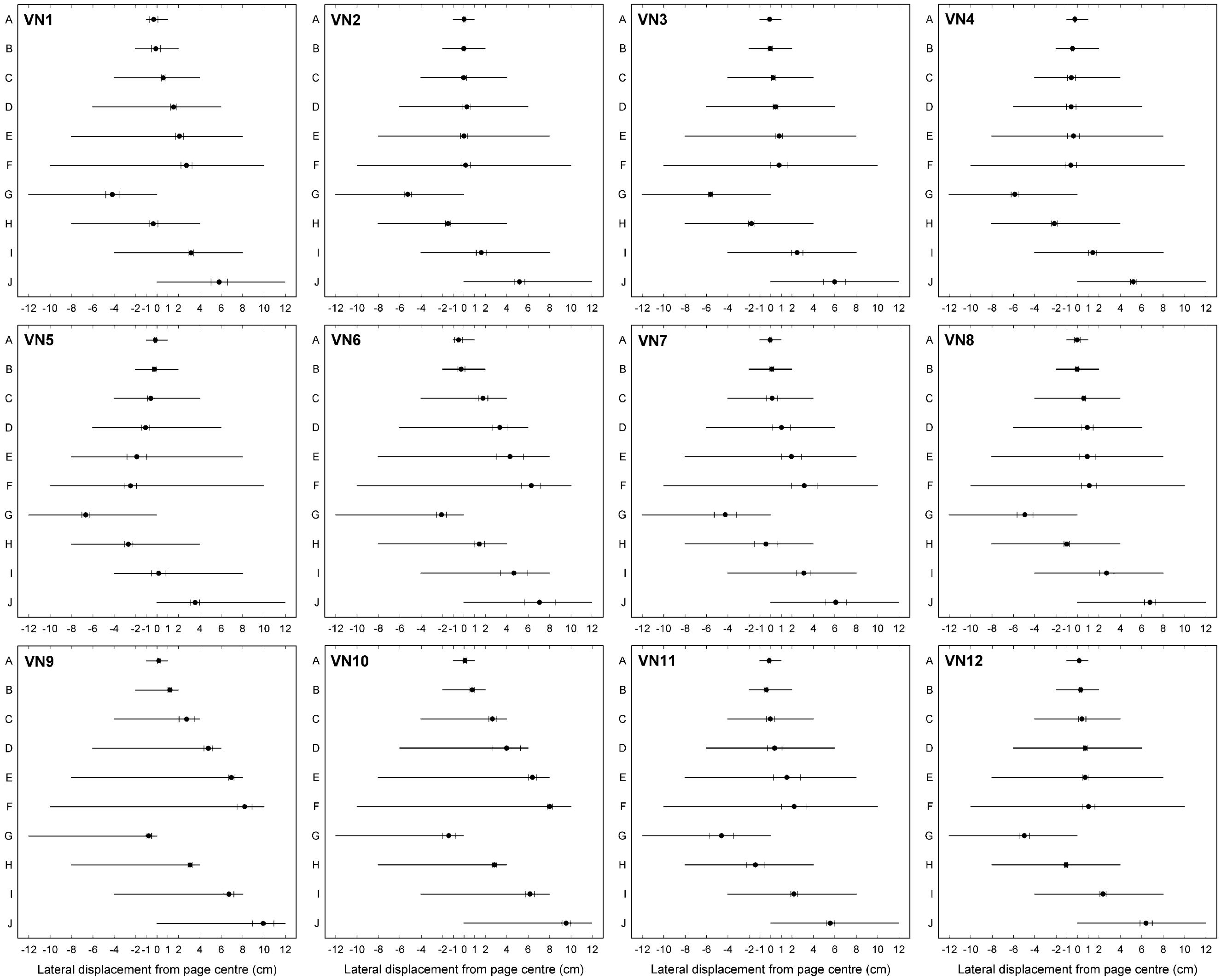

Fig. 5. Experiment 3. Individual data for patients VN1–VN12, showing mean P ± SD for each stimulus line (A–J).

for is listed additionally in Table 4. The overall accuracy of prediction is high, with 90% of the variance being captured on average. Accordingly, across the range of stimuli presented in Experiment 3, the bisection responses of neglect patients were predicted extremely well from a simple linear model based upon endpoint weightings. This model captures the classical effects of both line length and spatial position, including cross-over effects (Fig. 5).

3.4. Endpoint weightings and the standard task description

The classically observed effects of line length and spatial position on the bisection errors of neglect patients emerge naturally within an endpoint weightings analysis. In Eq. (3), the values of the endpoint weightings determine how bisection responses change with changes in the stimulus. The endpoint weightings thus capture the *dynamic* aspects of performance, whilst the value of constant k is additionally required in order to predict the precise response for a given stimulus.

Fig. 7a returns to the data from Experiment 1 to show the relationship between left and right endpoint weightings (cf. Fig. 3a). Each individual's dynamic bisection behaviour depends upon their combination of weightings, which can alternatively be characterised in terms of two composite measures derived from these weightings: endpoint weightings bias (EWB = $dP_R - dP_L$) and endpoint weightings sum (EWS = $dP_L - dP_R$). In Fig. 7a, the dashed line running from lower left to upper right is the line on which the two weightings are equal (EWB = 0); points above this line indicate a higher weighting for the left endpoint, and points below indicate a higher weighting for the right. The dotted line running from upper left to lower right is the line on which the weightings sum to one (EWS = 1); points above this line indicate a sum of greater than one, and points below indicate a sum of less than one. Patients with left neglect overwhelmingly occupy the quarter of the plot below both the dashed and dotted lines. That is, they have a higher weighting for the right endpoint than for the left (EWB > 0), and their weightings sum to less than one (EWS < 1).

Table 4
Analyses for individual patients in Experiment 3, showing endpoint weightings and constant k from best-fitting linear regression of mean P on L and R (Eq. (3))

VN patient	Bisection error (mm)	Endpoint weightings		k	r^2(P)	$r^2(B)$
		dP_L	dP_R			
VN1	10.94	0.25	0.59	−7.98	0.99	0.94
VN2	0.39	0.42	0.44	−0.44	1	0.92
VN3	3.13	0.44	0.54	−2.56	1	0.77
VN4	−5.04	0.47	0.45	−3.33	1	0.79
VN5	−12.68	0.55	0.29	2.69	0.99	0.94
VN6	25.96	0.01	0.76	−15.24	0.99	0.98
VN7	10.11	0.26	0.61	−8.10	0.99	0.90
VN8	6.91	0.41	0.56	−0.92	1	0.84
VN9	42.95	−0.01	0.90	−7.26	1	0.99
VN10	39.01	0.01	0.90	−9.89	0.1	0.99
VN11	5.15	0.29	0.56	−9.66	0.99	0.87
VN12	5.20	0.42	0.52	0.85	1	0.91
MEAN (SD)	11.00 (16.81)	0.29 (0.20)	0.59 (0.18)	−5.15 (5.34)	1 (0.01)	0.90 (0.07)

r^2(P), proportion of variance in mean P captured by Eq. (3). $r^2(B)$, proportion of variance in mean B captured by Eq. (4).

EWB and EWS are intuitively appealing measures within a weightings analysis. They also have interesting properties when considered within the standard task description. Simple algebra shows that EWB indexes the linear relationship between directional bisection error and stimulus line length (the slope of the line length effect is given by EWB / 2), whilst EWS indexes the linear relationship between directional bisection error and spatial position (the slope of

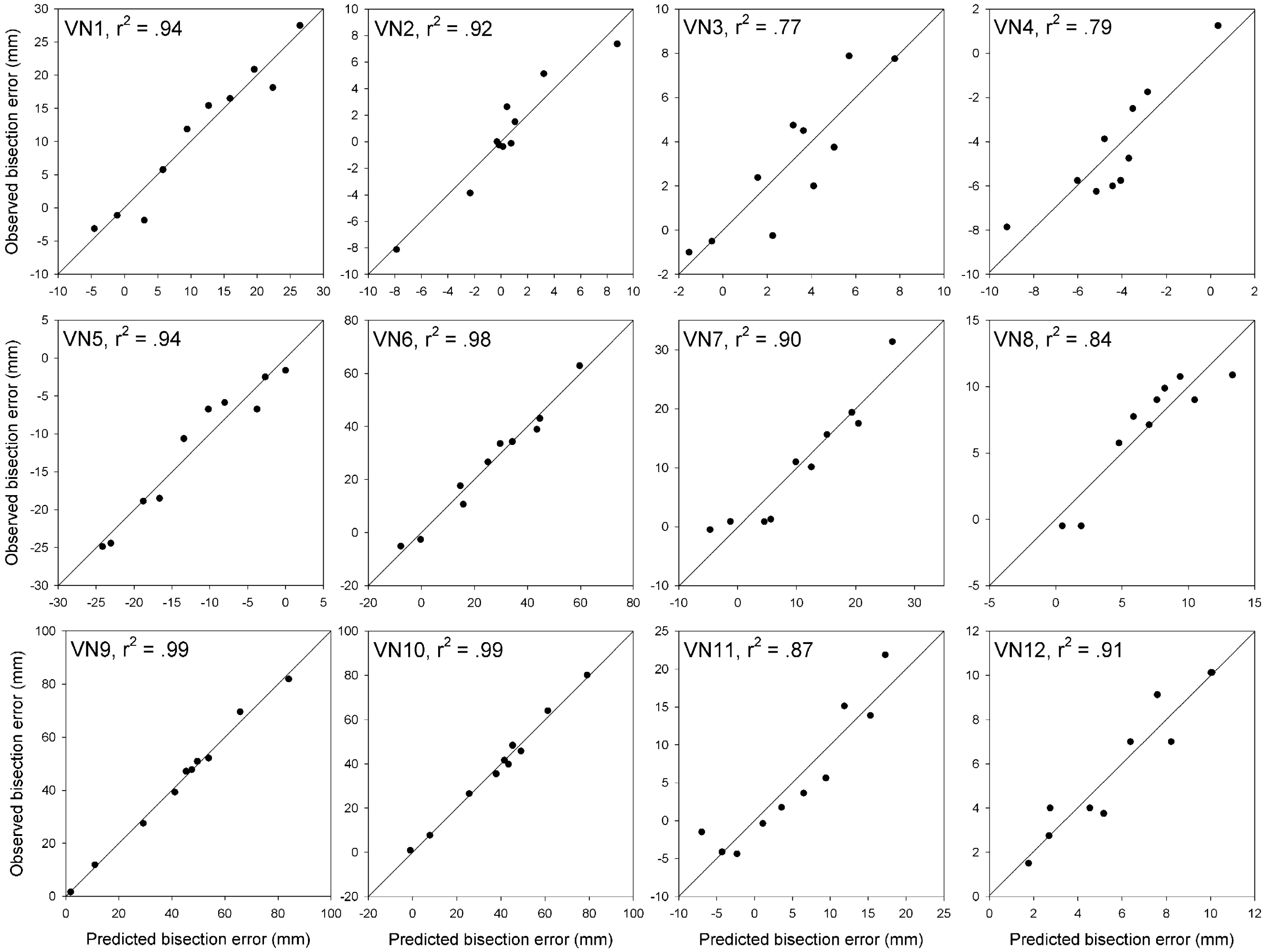

Fig. 6. Experiment 3. Individual scatterplots for patients VN1–VN12, relating bisection error predicted from Eq. (4) and observed bisection error.

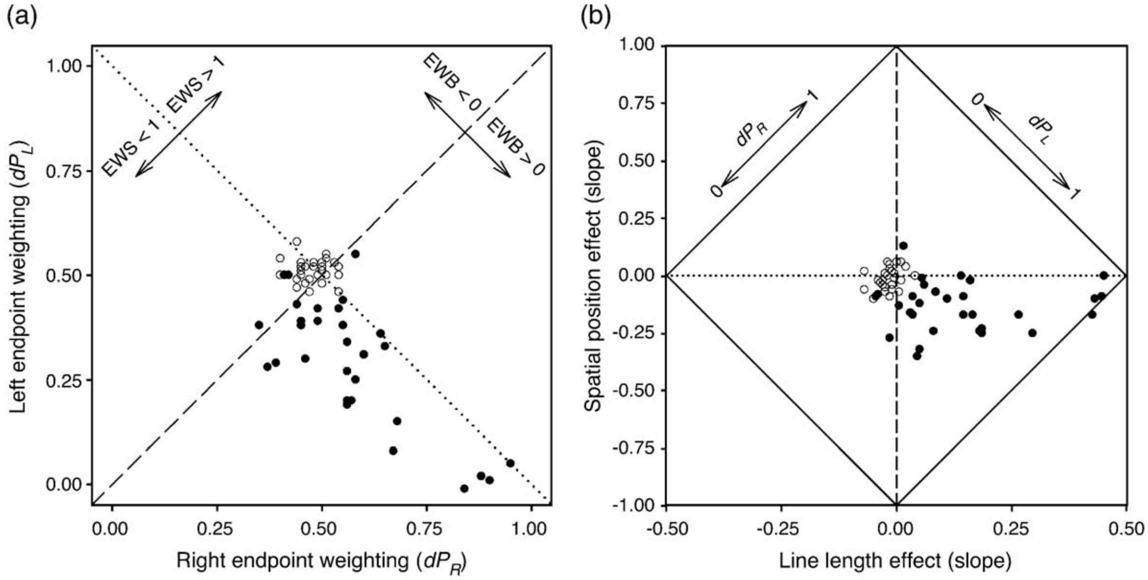

Fig. 7. Data from Experiment 1. (a) Scatterplot relating right and left endpoint weightings for HC subjects (open circles) and VN patients (filled circles). The dashed line represents the line on which the two endpoint weightings are equal, so that the endpoint weightings bias (EWB) equals zero. The dotted line represents the line on which the endpoint weightings sum (EWS) equals unity. (b) The data from Fig. 7a have been replotted in terms of the slopes of the line length and the spatial position effects within the standard task description. The enclosed diamond within this figure represents the original endpoint weightings axes from panel (a), rotated 45° anti-clockwise. This plot thus depicts the relationship between the endpoint weightings and the line length and spatial position effects of the standard model. See text for full details.

the spatial position effect is given by EWS − 1). This simple mapping between the weightings analysis and the standard task description is illustrated in Fig. 7b, in which the weightings from Fig. 7a have been replotted in terms of line length and spatial position effects (the diamond box within this figure represents the original weightings axes). It is evident that the characteristic pattern of endpoint weightings in left neglect translates inevitably into a positive line length effect (bisection errors become more rightward with increasing line length) and a negative spatial position effect (bisection errors become more leftward with increasingly rightward stimulus placement).

The ability to translate directly between alternative descriptive frameworks highlights the fact that the weightings analysis is mathematically equivalent to a standard model assuming independent linear influences of line length and spatial position on directional bisection error. Despite this formal equivalence, a major goal of the Discussion will be to argue that there are good reasons for adopting the weightings analysis in preference to the standard task description.

4. Discussion

The studies reported here differ from prior studies of line bisection in two important respects. First, the peripersonal locations of the left and right endpoints, rather than the conventional variables of line length and spatial location, have been treated as the independent variables of interest. Second, the tacit assumption that the bisection response represents the subjective midpoint has been relaxed, with the response coded simply as a location in peripersonal space rather than as an error relative to the true midpoint. We propose that these simple changes of emphasis may yield new insights into the character of neglect impairment on this task.

Experiment 1 showed that it is possible to consider the two endpoints of the line as having independent influences upon the placement of the response. This can be expressed in terms of a weighting for each endpoint — the proportion of the change in endpoint location that is reflected in the response. In patients with left visual neglect, the left endpoint weighting (dP_L) was reduced relative to the right endpoint weighting (dP_R), and the two endpoint weightings were related inversely across patients. An index of the asymmetry between the weightings (EWB) was found to distinguish neglect patients reliably from healthy controls, as well as being exquisitely sensitive to the slight leftward bias ('pseudoneglect') amongst controls.

Experiments 2 and 3 upheld the patterns observed in Experiment 1 across a wider range of bisection stimuli, including very short lines and laterally displaced lines. These experiments confirmed that the endpoint weightings constitute, to a first approximation, invariant features of an individual's performance, even for very short lines. This implies that the low weighting accorded to the left endpoint in neglect is not a simple consequence of a failure to explore fully leftwards. Finally, the response of a given patient to a given stimulus can be predicted with a high degree of accuracy from a simple linear equation in which the location of each endpoint is multiplied by its appropriate weighting, the products are summed, and a constant (k) is added (Eq. (3)). The hitherto disparate effects of line length and spatial position, including cross-over phenomena, are captured by this equation.

4.1. Advantages of the endpoint weightings analysis

The endpoint weightings analysis describes the line bisection data of neglect patients accurately. However, as has been emphasised, it does not provide any better fit to the data than a standard model assuming independent linear influences of line length and spatial position nor does it employ any fewer variables to achieve this fit. Nonetheless, it may be preferable to the standard model on a priori grounds of parsimony. The standard model, by casting directional error as its dependent variable, assumes that the bisection response is made at the subjective midpoint of the line. However, neglect patients are supremely bad at line bisection, and we may legitimately question whether many of them are capable of attempting the task as instructed. The eye movements made by such patients reinforce this point. Patients often fail to explore the stimulus line fully [34–36,38] and rarely make an intelligible bisection judgement even with regard to the scanned portion of the line [34,38,56]. In describing the behaviour of such patients, we can be certain only of the observable fact that they make a spatial response in compliance with the examiner's request. The weightings analysis makes no further assumptions but seeks simply to describe how that spatial response varies as a function of the stimulus. It is more parsimonious than the standard description because its starting assumptions are minimal and accordingly less likely to be mistaken.

A second advantage of the weightings analysis is that it leads naturally to a measure of neglect that is more sensitive than the core measure within the standard description. Neglect patients are characterised by an asymmetry between their endpoint weightings. EWB is a direct measure of this asymmetry and is more sensitive to neglect than is directional bisection error, at least for the stimuli used in Experiment 1. A possible objection to this argument is that, since EWB is also a measure of the slope of the line length effect within the standard model, we have merely demonstrated that the line length effect is a better indicator of neglect than is bisection error. However, it is important to note that there is a clear a priori reason for choosing EWB as the primary measure of neglect within the weightings analysis; by contrast, the slope of the line length effect has rarely been recognised as a useful, stimulus-independent, measure of bias within the standard model. One notable exception is provided by Adair et al., who cited a positive line length effect as evidence that their right-brain-damaged patient, who produced large leftward bisection errors, did not show true ipsilateral neglect [1]. No explanation, however, was given for why the line length effect should be such a good indicator of neglect. By contrast, the centrality of EWB within the weightings analysis is clear since it indexes an imbalance in the influences of two lateralised stimuli. As an aside, Adair et al.'s case study neatly demonstrates that a weightings analysis can unambiguously indicate left neglect, even when bisection errors are large and leftward (see also [50]).

Third, although the weightings analysis does not employ any fewer variables than the standard model, it arguably yields greater explanatory power from fewer theoretical constructs. Indeed, it provides a unified explanation for the effects of line length and spatial position using the single explanatory entity of an endpoint weighting. These weightings may well relate to the attentional mechanisms invoked to explain neglect on other tasks (see next section). This can be contrasted with existing interpretations of neglect bisection behaviour, which tend to be somewhat specific to bisection and to require additional post-hoc postulates to account for cross-over phenomena. It may also be noted that more than 25 years of research within the standard model has not produced any principled understanding of the relationship between spatial position and line length effects, yet this falls immediately out of a weightings analysis.

4.2. Theoretical interpretation of the endpoint weightings analysis

So far, we have treated the weightings analysis as a theoretically neutral quantitative description of bisection data. This novel analytic framework may have value in its own right, but the deeper question is whether its concepts correspond to neuropsychological reality any more directly than do those of the standard model. In order to address this question, we need to provide some theoretical clothing for the bare task description.

At face value, the endpoints model is compatible with an interpretation of rightward bisection error in the familiar terms of perceptual distortion [9,52–55]. By this account, the endpoint weightings would index the degree to which length is misperceived at either end of the line. If length is perceived veridically and bisection judgements are accurate, then each endpoint will have a weighting of 0.5. However, if neglect patients perceive space as contracted on the left and expanded on the right, then the weighting for the left endpoint will be lower than 0.5 and the weighting for the right endpoint will be higher. Within this framework, EWB would measure the gradient of size distortion.

There are, however, problems with this interpretation, over and above its implicit reinstatement of the assumption that neglect patients respond to their subjective midpoint. First, perceptual distortion theories typically assume that the distortion extends as a gradient across space, so that its effects become more pronounced at more eccentric locations. This assumption seems incompatible with the observed invariance of the endpoint weightings across changes in stimulus length and spatial position. Similarly, it is unclear whether a single gradient of perceptual distortion could account for the effects of spatial position as well as those of line length, particularly considering that these effects are uncorrelated in real patients (Fig. 7b). Finally, if EWB is a direct measure of perceptual distortion and errors of bisection also result from size distortion, then we would expect a near-perfect linear correlation between these measures. In fact, the relationship between EWB and bisection error, whilst highly significant, is far from perfect and is non-linear (Spearman's $\rho = 0.77$; Fig. 3b).

At present, our favoured interpretation follows Kinsbourne's qualitative account of line bisection [41]. Kinsbourne proposed that neglect may limit the capacity to attend simultaneously to locations on both sides of space, rendering the patient incapable of making a normal bisection judgement. Instead, patients may respond at some distance from the right endpoint of the line without regard to any perceived terminus on the left. The present study shows that it is possible to develop a quantitative description of neglect performance that is compatible with this proposal. That is, line bisection data can be modelled accurately without assuming that the subject maintains any overview of the bisection stimulus or necessarily perceives a subjective midpoint.

The strength of Kinsbourne's account is most strongly seen in those patients who made their bisection responses apparently without influence from the left endpoint of the line. These cases are also consistent with Koyama et al.'s claim that patients with severe neglect bisect without regard to the left endpoint [42]. We did not observe any patients who responded at a constant *distance* from the right endpoint, as proposed by Koyama et al., but a constant linear relationship was always maintained between the spatial response and the right endpoint. Koyama et al. further suggested that patients with severe neglect differ *qualitatively* in their bisection strategy from those with more mild impairments. However, the weightings analysis captures the behaviour of patients with more mild asymmetries as well as those in whom the left endpoint has zero weighting. It may thus be possible to interpret the responses of all of our patients (and perhaps even healthy subjects) within a similar conceptual framework.

Within Kinsbourne's model, a zero weighting for the left endpoint would reflect the fact that, even if the left endpoint has been viewed, the patient is unable to keep its location in mind whilst simultaneously attending to the location of right endpoint. Their response can thus be made only with respect to the right endpoint. One notable feature of this account is that it requires no additional postulates to explain cross-over bisections. Since the patient cannot refer to the left endpoint of the line, they will produce leftward errors of bisection provided only that they respond at a sufficient distance from the right endpoint. In order to explain the behaviour of patients with more mild asymmetries, in whom the left endpoint has a non-zero weighting, we might propose that the ability to attend to the left endpoint at the same time as the right is diminished but not destroyed, so that its location is represented with less certainty, thereby reducing its influence.

There are different ways in which we could conceptualise these effects. One hypothesis is that the patient's awareness of the bisection stimulus is prone to a form of 'representational extinction', in which the right endpoint out-competes the left endpoint for limited attentional resources. On this account, the endpoint weightings asymmetry (EWB) could be considered as a measure of lateral attentional bias. An alternative hypothesis is that the apparent inability to represent the left endpoint location accurately might be attributable to a failure of spatial working memory for previously visited locations [32,44,60,71], which would prevent patients from storing endpoint locations accurately across saccadic or attentional shifts (see [59] for a related suggestion). In this account, the impairment of spatial memory might itself be non-lateralised, but the tendency for neglect patients to attend preferentially rightwards would cause the representation of the left endpoint location to be the more severely compromised.

4.3. Empirical predictions of the endpoint weightings analysis

The endpoint weightings analysis yields a number of testable predictions that would not be generated by the standard model. First, the inverse relationship between endpoint weightings across patients (Fig. 3a) suggests a competitive lateral bias of attention favouring rightward stimuli [41]. A true competitive bias, however, would involve an antagonistic relationship between endpoint weightings *within patients*, such that manipulations increasing attentional allocation to one endpoint would entail a proportional decrease of attention to the other. Lateral attentional cueing (or other manipulations influencing lateral attentional allocation) should thus produce changes in EWB but not in EWS, thereby modifying the slope of the line length effect (EWB/2) but having little or no effect upon the slope of the spatial position effect ($1 - \text{EWS}$).

Second, if EWB is considered to index the lateral bias of attention, then the most straightforward interpretation of EWS would be that it indexes the total attentional resources brought to the task. The fact that EWS is typically less than unity would reflect a global depletion in attentional resources. This might be conceptualised in terms of deficient arousal, which is known to be associated with right hemisphere damage (e.g. [30,43]). Deficient arousal has been identified as an important factor colouring the expression of neglect symptoms, but it is neither necessary nor sufficient for neglect [62]. This raises the interesting possibility that, whilst the classically observed effects of line length on bisection errors (EWB/2) may reflect the lateral attentional bias of neglect, the classically observed effects of spatial position ($1 - \text{EWS}$) may not be specific to neglect and might instead reflect a global reduction of attentional resources. The lack of correlation between EWB and EWS amongst our patients (Fig. 7) lends some circumstantial support to this idea. The critical prediction, however, is that

EWS (i.e. the slope of the spatial position effect) should correlate with measures of arousal and may additionally be modifiable by manipulations of arousal (cf. [63]).

The endpoint weightings analysis is unique in bringing together the line length and spatial position effects. Fig. 7 illustrates that, for a given patient, the slopes of the line length and spatial position effects emerge naturally from the two endpoint weightings. However, assuming that the minimum possible influence that an endpoint can have upon the bisection response is zero and that the maximum weighting is one, then only certain combinations of line length and spatial position effects should be possible. Specifically, no patient should ever be found with a combination of line length and spatial position effects that places them outside the central diamond depicted in Fig. 7b. This diamond implies that, as the slope of the line length effect approaches its extreme values, the range of possible spatial position effects reduces and vice versa. By contrast, there is no clear reason within the standard model for assuming such strict limits on behaviour. The existence of a patient performing clearly outside the 'diamond of possibility', depicted in Fig. 7b, would falsify the endpoint weightings analysis as a general account of line bisection behaviour in neglect.

4.4. Summary, outstanding issues and conclusions

The purpose of this paper has been to introduce a novel framework for describing and understanding line bisection behaviour, which does not rely on the assumption that the subject is able to perform the task as the examiner has conceived it (i.e. by surveying the stimulus line and estimating the midpoint). Within this new framework, some patients with left visual neglect appear to be entirely uninfluenced by the location of the left endpoint of the line, responding exclusively with reference to the right endpoint. In less severe cases, the left endpoint does have a reliable influence, but this is almost always less than that of the right. For each patient, the influences of the two endpoints can be quantified as weightings, which remain relatively constant across stimuli. These weightings predict the patient's dynamic pattern of bisection behaviour: that is, how their response changes with changes in the stimulus. To predict the precise response position for a given stimulus additionally requires the value of constant k (Eq. (3)).

As a quantitative model of bisection behaviour, the endpoint weightings analysis is remarkably accurate, given its simplicity, and has advantages of parsimony over the standard model. However, several limitations of the analysis, in its present form, must be recognised. First, it has been evaluated across a limited set of stimuli only, all of which were presented within an A4 area in front of the body midline. It seems likely that the invariance of the weightings (and thus the linearity of the model) would break down if stimuli were presented over a wider area, especially if the shifts in stimulus placement encouraged the subject to turn their head and/or trunk and to redefine their workspace. This would not necessarily render the weightings analysis invalid, but it might make its application more complex. A second limitation of the model is that it makes no predictions regarding response variability for a given stimulus, which is an important feature of performance that ultimately needs explaining. Additionally, we have not yet proposed any theoretical interpretation of constant k. Further development of the model will be required in order to address these issues.

Finally, although the weightings analysis can be applied to any subject's data, it is an open question whether its theoretical implications will be similarly generalisable or will apply only to a subset of neglect patients (cf. [42]). However, even a limited applicability of the model would represent a significant advance in our understanding of neglect bisection behaviour. Moreover, regardless of the value of any specific theoretical hypotheses developed here, the weightings analysis may be a valuable research tool in its own right. By encouraging us to view the bisection task from a novel perspective, it focuses attention on aspects of performance that are not normally considered and may thereby generate fresh insights into the nature of neglect impairment on this ubiquitous clinical task.

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References

[1] J.C. Adair, A. Chatterjee, R.L. Schwartz, K.M. Heilman, Ipsilateral neglect: reversal of bias or exaggerated cross-over phenomenon? Cortex 34 (1998) 147–153.

[2] M. Axenfeld, Hemianopische Gesichtsfeldtstörungen nach Schädelschüssen, Klin. Monatsbl. Augenheilkd. 55 (1915) 126–143.

[3] J. Binder, R. Marshall, R. Lazar, J. Benjamin, J.P. Mohr, Distinct syndromes of hemineglect, Arch. Neurol. 49 (1992) 1187–1194.

[4] E. Bisiach, E. Capitani, A. Colombo, H. Spinnler, Halving a horizontal segment: a study on hemisphere-damaged patients with cerebral focal lesions, Schweiz. Arch. Neurol. Neurochir. Psychiatr. 118 (1976) 199–206.

[5] E. Bisiach, C. Bulgarelli, R. Sterzi, G. Vallar, Line bisection and cognitive plasticity of unilateral neglect of space, Brain Cogn. 2 (1983) 32–38.

[6] E. Bisiach, G. Geminiani, A. Berti, M.L. Rusconi, Perceptual and premotor factors of unilateral neglect, Neurology 40 (1990) 1278–1281.

[7] E. Bisiach, M.L. Rusconi, V.A. Peretti, G. Vallar, Challenging current accounts of unilateral neglect, Neuropsychologia 32 (1994) 1431–1434.

[8] E. Bisiach, L. Pizzamiglio, D. Nico, G. Antonucci, Beyond unilateral neglect, Brain 119 (1996) 851–857.

[9] E. Bisiach, R. Ricci, M.N. Modona, Visual awareness and anisometry of space representation in unilateral neglect: a panoramic investigation by means of a line extension task, Conscious. Cogn. 7 (1998) 327–355.

[10] D. Bowers, K.M. Heilman, Pseudoneglect: effects of hemispace on a tactile line bisection task, Neuropsychologia 18 (1980) 491–498.

[11] C.M. Butter, V.W. Mark, K.M. Heilman, An experimental analysis of factors underlying neglect in line bisection, J. Neurol. Neurosurg. Psychiatry 51 (1988) 1581–1583.

[12] A. Chatterjee, Cross-over, completion and confabulation in unilateral spatial neglect, Brain 118 (1995) 455–465.

[13] A. Chatterjee, Spatial anisometry and representational release in neglect, in: H.-O. Karnath, A.D. Milner, G. Vallar (Eds.), The Cognitive and Neural Bases of Spatial Neglect, Oxford Univ. Press, New York, 2002, pp. 167–180.

[14] A. Chatterjee, B.M. Dajani, R.J. Gage, Psychophysical constraints on behavior in unilateral spatial neglect, Neuropsychiatry Neuropsychol. Behav. Neurol. 7 (1994) 267–274.

[15] A. Chatterjee, M. Mennemeier, K.M. Heilman, The psychophysical power law and unilateral spatial neglect, Brain Cogn. 25 (1994) 92–107.

[16] S. Chokron, J.M. Bernard, M. Imbert, Length representation in normal and neglect subjects with opposite reading habits studied through a line extension task, Cortex 33 (1997) 47–64.

[17] H.B. Coslett, D. Bowers, E. Fitzpatrick, B. Haws, K.M. Heilman, Directional hypokinesia and hemispatial inattention in neglect, Brain 113 (1990) 475–486.

[18] M. Critchley, The Parietal Lobes, E Arnold and Company, London, 1953.

[19] H.C. Dijkerman, R.D. McIntosh, A.D. Milner, Y. Rossetti, C. Tilikete, R.C. Roberts, Ocular scanning and perceptual size distortion in hemispatial neglect: effects of prism adaptation and sequential stimulus presentation, Exp. Brain Res. 153 (2003) 220–230.

[20] F. Doricchi, G. Galati, L. DeLuca, D. Nico, F. D'Olimpio, Horizontal space misrepresentation in unilateral brain damage: I. Visual and proprioceptive-motor influences in left unilateral neglect, Neuropsychologia 40 (2002) 1107–1117.

[21] S. Ferber, H.O. Karnath, How to assess spatial neglect—Line bisection or cancellation tasks? Neurosci. Biobehav. Rev. 23 (2001) 599–607.

[22] G. Gainotti, P. Messerli, R. Tissot, Qualitative analysis of unilateral spatial neglect in relation to laterality of cerebral lesions, J. Neurol. Neurosurg. Psychiatry 35 (1972) 545–550.

[23] P.W. Halligan, J.C. Marshall, How long is a piece of string—A study of line bisection in a case of visual neglect, Cortex 24 (1988) 321–328.

[24] P.W. Halligan, J.C. Marshall, Line bisection in visuo-spatial neglect—Disproof of a conjecture, Cortex 25 (1989) 517–521.

[25] P.W. Halligan, J.C. Marshall, Perceptual cueing and perceptuo-motor compatibility in visuo-spatial neglect—A single case-study, Cogn. Neuropsychol. 6 (1989) 423–435.

[26] P.W. Halligan, J.C. Marshall, Left visuospatial neglect—A meaningless entity, Cortex 28 (1992) 525–535.

[27] M. Harvey, A.D. Milner, R.C. Roberts, An investigation of hemispatial neglect using the landmark task, Brain Cogn. 27 (1995) 59–78.

[28] M. Harvey, T. Kramer-McCaffery, L. Dow, P.J.S. Murphy, I.D. Gilchrist, Categorisation of 'perceptual' and 'premotor' neglect patients across different tasks: is there strong evidence for a dichotomy? Neuropsychologia 40 (2002) 1387–1395.

[29] K.M. Heilman, E. Valenstein, Mechanisms underlying hemispatial neglect, Ann. Neurol. 5 (1979) 166–170.

[30] K.M. Heilman, T. Van Den Abell, Right hemisphere dominance for mediating cerebral activation, Neuropsychologia 17 (1979) 315–321.

[31] M. Husain, J.B. Mattingley, C. Rorden, C. Kennard, J. Driver, Distinguishing sensory and motor biases in parietal and frontal neglect, Brain 123 (2000) 1643–1659.

[32] M. Husain, S.K. Mannan, T. Hodgson, E. Wojciulik, J. Driver, C. Kennard, Impaired spatial working memory across saccades contributes to abnormal search in parietal neglect, Brain 124 (2001) 941–952.

[33] L. Irving-Bell, M. Small, A. Cowey, A distortion of perceived space in patients with right-hemisphere lesions and visual hemineglect, Neuropsychologia 37 (1999) 919–925.

[34] S. Ishiai, T. Furukawa, H. Tsukagoshi, Visuospatial processes of line bisection and the mechanisms underlying unilateral spatial neglect, Brain 112 (1989) 1485–1502.

[35] S. Ishiai, M. Sugishita, K. Mitani, M. Ishizawa, Leftward search in left unilateral spatial neglect, J. Neurol. Neurosurg. Psychiatry 55 (1992) 40–44.

[36] S. Ishiai, K. Seki, Y. Koyama, S. Gono, Ineffective leftward search in line bisection and mechanisms of left unilateral spatial neglect, J. Neurol. 243 (1996) 381–387.

[37] S. Ishiai, Y. Koyama, K. Seki, Significance of paradoxical leftward error of line bisection in left unilateral spatial neglect, Brain Cogn. 45 (2001) 238–248.

[38] S. Ishiai, et al. Approaches to subjective midpoint of horizontal lines in unilateral spatial neglect. Cortex (in press).

[39] G. Jewell, M.E. McCourt, Pseudoneglect: a review and meta-analysis of performance factors in line bisection tasks, Neuropsychologia 38 (2000) 93–110.

[40] G. Kerkhoff, Multiple perceptual distortions and their modulation in leftsided visual neglect, Neuropsychologia 38 (2000) 1073–1086.

[41] M. Kinsbourne, Orientational bias model of unilateral neglect: evidence from attentional gradients within hemispace, in: I.H. Robertson, J.C. Marshall (Eds.), Unilateral Neglect: Clinical and Experimental Studies, Lawrence Erlbaum Associates, Hove, UK, 1993, pp. 63–86.

[42] Y. Koyama, S. Ishiai, K. Seki, T. Nakayama, Distinct processes in line bisection according to severity of left unilateral spatial neglect, Brain Cogn. 35 (1997) 271–281.

[43] E. Làdavas, M. Del Pesce, G.R. Mangun, M.S. Gazzaniga, Variations in attentional bias of the disconnected cerebral hemispheres, Cogn. Neuropsychol. 11 (1994) 57–74.

[44] P. Malhotra, H.R. Jager, A. Parton, R. Greenwood, E.D. Playford, M.M. Brown, et al., Spatial working memory capacity in unilateral neglect, Brain 128 (2005) 424–435.

[45] J.C. Marshall, P.W. Halligan, When right goes left—An investigation of line bisection in a case of visual neglect, Cortex 25 (1989) 503–515.

[46] J.C. Marshall, P.W. Halligan, Line bisection in a case of visual neglect—Psychophysical studies with implications for theory, Cogn. Neuropsychol. 7 (1990) 107–130.

[47] J.B. Mattingley, J. Driver, Distinguishing sensory and motor deficits after parietal damage: an evaluation of response selection biases in unilateral neglect, in: P. Thier, H.-O. Karnath (Eds.), Parietal Lobe Contributions to Orientation in 3d Space, Springer, Heidelberg, 1997, pp. 309–337.

[48] R. McGlinchey-Berroth, D.P. Bullis, W.P. Milberg, M. Verfaellie, M. Alexander, M. D'Eposito, Assessment of neglect reveals dissociable behavioral but not neuroanatomical subtypes, J. Int. Neuropsychol. Soc. 2 (1996) 441–451.

[49] R.D. McIntosh, K.I. McClements, H.C. Dijkerman, A.D. Milner, "Mind the gap": the size–distance dissociation in visual neglect is a cueing effect, Cortex 40 (2004) 339–346.

[50] R.D. McIntosh, K.I. McClements, H.C. Dijkerman, D. Birchall, A.D. Milner, Preserved obstacle avoidance during reaching in patients with left visual neglect, Neuropsychologia 42 (2004) 1107–1117.

[51] M. Mennemeier, S.Z. Rapcsak, C. Pierce, E. Vezey, Crossover by line length and spatial location, Brain Cogn. 47 (2001) 412–422.

[52] A.D. Milner, Animal models for the syndrome of spatial neglect, in: M. Jeannerod (Ed.), Neurophysiological and Neuropsychological Aspects of Spatial Neglect, Elsevier, Amsterdam, 1987, pp. 259–288.

[53] A.D. Milner, M. Harvey, Distortion of size perception in visuospatial neglect, Curr. Biol. 5 (1995) 85–89.

[54] A.D. Milner, M. Harvey, R.C. Roberts, S.V. Forster, Line bisection errors in visual neglect—Misguided action or size distortion? Neuropsychologia 31 (1993) 39–49.

[55] A.D. Milner, M. Harvey, C.L. Pritchard, Visual size processing in spatial neglect, Exp. Brain Res. 123 (1998) 192–200.

[56] K. Misonou, S. Ishiai, K. Seki, Y. Koyama, N. Nakano, How do patients with neglect see a horizontal line? Analysis of performances in coloured line bisection task, J. Neurol. 251 (2004) 696–703.

[57] P. Nichelli, M. Rinaldi, R. Cubelli, Selective spatial attention and length representation in normal subjects and in patients with unilateral spatial neglect, Brain Cogn. 9 (1989) 57–70.

[58] D. Nico, Detecting directional hypokinesia: the epidiascope technique, Neuropsychologia 34 (1996) 471–474.

[59] L. Pisella, J.B. Mattingley, The contribution of spatial remapping impairments to unilateral visual neglect, Neurosci. Biobehav. Rev. 28 (2004) 181–200.

[60] L. Pisella, N. Berberovic, J.B. Mattingley, Impaired working memory for location but not for colour or shape in visual neglect: a comparison of parietal and non-parietal lesions, Cortex 40 (2004) 379–390.

[61] M.J. Riddoch, G.W. Humphreys, The effect of cueing on unilateral neglect, Neuropsychologia 21 (1983) 589–599.

[62] I.H. Robertson, The relationship between lateralised and non-lateralised attentional deficits in unilateral neglect, in: I.H. Robertson, J.C. Marshall (Eds.), Unilateral Neglect: Clinical and Experimental Studies, Lawrence Erlbaum Associates, Hove, UK, 1993, pp. 257–275.

[63] I.H. Robertson, R. Tegnér, K. Tham, A. Lo, I. Nimmo-Smith, Sustained attention training for unilateral neglect: theoretical and rehabilitation implications, J. Clin. Exp. Neuropsychol. 17 (1995) 416–430.

[64] S. Savazzi, C. Frigo, D. Minuto, Anisometry of space representation in neglect dyslexia, Brain Res. Cogn. Brain. Res. 19 (2004) 209–218.

[65] T. Schenkenberg, D.C. Bradford, E.T. Ajax, Line bisection and unilateral visual neglect in patients with neurologic impairment, Neurology 30 (1980) 509–517.

[66] F. Schubert, J. Spatt, Double dissociations between neglect tests: possible relation to lesion site, Eur. Neurol. 45 (2001) 160–164.

[67] S.S. Stevens, Measurement and man, Science 127 (1958) 383–389.

[68] R. Tegnér, M. Levander, The influence of stimulus properties on visual neglect, J. Neurol. Neurosurg. Psychiatry 54 (1991) 882–887.

[69] R. Tegnér, M. Levander, Through a looking-glass—A new technique to demonstrate directional hypokinesia in unilateral neglect, Brain 114 (1991) 1943–1951.

[70] B. Wilson, J. Cockburn, P.W. Halligan, Behavioural Inattention Test, Thames Valley Test Company, Titchfield, Hampshire, UK, 1987.

[71] E. Wojciulik, M. Husain, K. Clarke, J. Driver, Spatial working memory deficit in unilateral neglect, Neuropsychologia 39 (2001) 390–396.