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Preserved obstacle avoidance during reaching in patients with left visual neglect

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Abstract

We asked 12 patients with left visual neglect to bisect the gap between two cylinders or to reach rapidly between them to a more distal target zone. Both tasks demanded a motor response but these responses were quite different in nature. The bisection response was a communicative act whereby the patient indicated the perceived midpoint. The reaching task carried no imperative to bisect the gap, only to maintain a safe distance from either cylinder while steering to the target zone. Optimal performance on either task could only be achieved by reference to the location of both cylinders. Our analysis focused upon the relative influence of the left and right cylinders on the lateral location of the response. In the bisection task, all neglect patients showed qualitatively the same asymmetry, with the left cylinder exerting less influence than the right. In the reaching task, the neglect group behaved like normal subjects, being influenced approximately equally by the two cylinders. This was true for all bar two of the patients, who showed clear neglect in both tasks. We conclude that the visuomotor processing underlying obstacle avoidance during reaching is preserved in most patients with left visual neglect.
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1. Introduction

Patients with visual neglect fail to report or respond to visual stimuli from one side of space, typically the left side following right hemisphere damage. Neglect is generally studied as a disorder of spatial cognition, though it is widely recognised that some of its symptoms could arise from impairments in the organisation of motor responses. Directional abnormalities in the movements of the ipsilesional arm of visual neglect patients are well documented. Contralesionally directed movements may be retarded (Heilman, Bowers, Coslett, Whelan, & Watson, 1985; Mattingley, Bradshaw, & Phillips, 1992), slowed (Mattingley et al., 1992) or reduced in amplitude (Meador, Loring, Baron, Rogers, & Kimpel, 1988). It has also been reported that the visually guided reaching movements of left neglect patients are curved abnormally rightwards (Goodale, Milner, Jakobson, & Carey, 1990; Harvey, Milner, & Roberts, 1994; Jackson, Newport, Husain, Harvey, & Hindle, 2000) although several studies have failed to replicate this observation (Chieffi, Gentilucci, Allport, Sasso, & Rizzolatti, 1993; Harvey et al., 2002; Karnath, Dick, & Konczak, 1997; Perenin, 1997).

The existence of movement abnormalities in neglect, however, does not itself show that these symptoms have a motor origin. Special techniques are required to tease apart input- ("perceptual") and output-related ("premotor") aspects of neglect (reviewed by Mattingley & Driver, 1997). The distinction between input and output biases in neglect has been hugely influential since it was proposed by Heilman and Watson (1977). It is therefore crucial to state at the outset that the present paper will not be concerned with further pursuing this distinction. Instead, we adopt a different approach based on evidence that there are parallel routes of information processing from stimulus to response, and that different routes subserve different behavioural functions. Rather than investigating whether input and output biases can be disentangled, we wish to investigate whether parallel pathways from vision to action may be differentially affected by the biases that neglect patients exhibit.

Milner and Goodale (1995) proposed a cardinal distinction between the processing giving rise to conscious visual awareness and the processing underlying the direct visual

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guidance of actions. They identified these processing pathways anatomically with the ventral and dorsal streams, which diverge from occipital cortex and terminate in the inferior temporal and superior parietal cortices respectively. Additionally, they hypothesized that the symptoms of neglect reflect a malfunction in a high-level representational structure where the products of ventral stream processing are combined spatially and used as a basis for visual thought (see also Milner, 1997). Consistent with this, the focus for neglect-inducing lesions lies ventrally in the inferior parietal lobe (Vallar, 1993; Vallar & Perani, 1986), and may even overlap into the temporal lobe (Karnath, Ferber, & Himmelbach, 2001, but see Mort et al., 2003), while the visuomotor areas lie superiorly in the parietal cortex (Culham et al., 2003; Culham & Kanwisher, 2001; Perenin & Vighetto, 1988). Milner and Goodale's hypothesis suggests that many visual neglect patients who are subject to spatially disordered perception may code spatial parameters veridically when executing goal-directed actions, since this would be accomplished by intact dorsal stream structures. That is, the effects of neglect on visual experience should not necessarily compromise the implicit visuospatial processing required for the guidance of action.

In apparent contradiction to Milner and Goodale's (1995) hypothesis, Behrmann and Meegan (1998) have claimed that information from the neglected side is processed minimally, if at all, in the visuomotor domain. This conclusion was based on an experiment in which six left neglect patients fixated centrally and were required to reach from a central position to targets illuminated on the left or right. Targets were presented alone or with a distractor of a different colour on the opposite side. Subjects took longer to initiate responses to targets accompanied by a distractor but, relative to normal subjects, neglect patients had a reduced cost for left-sided distractors and an increased cost for right-sided distractors. Similar asymmetrical patterns of distractor interference in visuomotor tasks have been reported several times (Corben, Mattingley, & Bradshaw, 2001; Husain, Mattingley, Rorden, Kennard, & Driver, 2000; Mattingley et al., 1998). However, it is far from clear that these effects were visuomotor in nature. In all cases, a prior requirement for responding was the explicit perceptual discrimination of target from distractor, so any effect of distractors on target identification would have influenced response initiation time. Related concerns apply to a report of exaggerated early veering towards ipsilateral distractors in the reach-to-grasp movements of a recovered neglect patient (Chieffi et al., 1993). Subjects were required to grasp the target object as rapidly as possible following stimulus exposure. In this situation, reaction times could be optimised by initiating a spatially intermediate reaching response upon stimulus detection and updating it once perceptual discrimination of target from distractor had been achieved. Again, although a visuomotor response was employed, the distractor interference effects could have had a perceptual origin.

In order to exclude confounding effects of explicit perceptual processing, we have explored Milner and Goodale's (1995) proposals regarding neglect by using a task designed to tap implicit visuomotor competence. Where this strategy has been adopted previously, the evidence has been broadly supportive of Milner and Goodale's ideas. Robertson, Nico and Hood (1995) required neglect patients to point to the middle of horizontal rods or, in separate blocks of trials, to reach out to pick them up. The pointing response communicated an explicit bisection judgement but the reaching response required an implicit midpoint computation in order to grasp the rod at its centre of mass in preparation for a stable lift. Patients were prevented from actually lifting the rod, and never received feedback on their performance in either task. Nonetheless, the classic rightward errors made in the bisection task were significantly reduced by the intention to pick the rod up. Robertson et al. concluded that this intention allowed the patients to access dorsal stream spatial computations that were relatively free from neglect (see also Edwards & Humphreys, 1999). In a similar vein, Pritchard, Milner, Dijkerman and MacWalter (1997) reported a neglect patient who underestimated the size of cylindrical objects in her left body hemispace when required to indicate their size, yet who scaled her anticipatory grip aperture appropriately when picking them up. Subsequent studies have replicated the accurate calibration of grip in neglect patients (Harvey et al., 2002; McIntosh, Pritchard, Dijkerman, Milner, & Roberts, 2002), although the selection of grasp points on more complex objects has recently been shown to be affected by neglect (Marotta, McKeeff, & Behrmann, 2003) (see Section 4).

In the present study, we have followed the general approach of assessing the visuospatial processing of neglect patients under explicit perceptual and implicit visuomotor conditions. Patients were asked to move their hand between two upright cylinders, one located on either side of the midline, under two different instructions. In one task they were asked to place their index finger at the midpoint of the gap between the two cylinders—an explicit bisection judgement. In the other task they were told simply to move their finger to any point within a laterally extended target zone beyond the cylinders. This reaching response carries the implicit requirement of being executed so as to minimise the risk of collision with either cylinder (Tresilian, 1998). Our pilot studies with normal subjects indicated that the optimal path passes on average approximately midway between the two cylinders; but this superficial resemblance to bisection behaviour is dependent upon the particular spatial parameters employed. The important correspondence between the bisection and reaching tasks is that optimal performance requires the subject to take account simultaneously of objects on either side of space. By varying the locations of the left and right cylinders independently, we were able to quantify the influence that each cylinder had on the responses of each subject.

Data on these tasks from seven neglect patients and controls were summarised by Milner and McIntosh (2002). A

clear dissociation between the expression of neglect in the two tasks was reported. In the bisection task, neglect patients were less sensitive to the location of the left cylinder than to the location of the right cylinder but, like normal subjects, they were influenced equally by the two cylinders when reaching between them. The present paper provides a full report of this experiment subsequent to the inclusion of a further five neglect patients.

2. Methods

2.1. Subjects

Twelve patients with left visual neglect following unilateral right hemisphere stroke, and 12 healthy controls, took part in this experiment. All subjects were right-handed by self-report. The mean age of the neglect group was 67.9 years (S.D. 7.5 years) and the mean age of the control group was 66.8 years (S.D. 9.7 years) [$t(22) = 0.31$, $P = 0.76$]. All patients showed neglect on at least three of the following diagnostic tests: line crossing, star cancellation, representational drawing, line bisection (conventional sub-tests of the Behavioural Inattention Test (BIT), Wilson, Cockburn, & Halligan, 1987) and a five-item scene copying task adapted from Gainotti, Messerli, and Tissot (1972). For line crossing and star cancellation, left neglect was diagnosed where the total number of targets cancelled fell below the standardised BIT cut-off score and at least 10% fewer targets were cancelled on the left than on the right (Robertson et al., 1994). For line bisection, left neglect was diagnosed where the total score fell below the BIT cut-off and the mean bisection error was rightward and greater than or equal to 10% of the line half-length. For representational drawing, neglect was identified by a clear poverty of left-sided details on one or more of the three items copied. For scene copying, neglect was identified by the omission of one or more item on the left or a clear poverty of left-sided details on one or more item. Screening scores and clinical details for the patients are summarised in Table 1. (Grouped data for patients N1–N7 in Table 1 were originally reported by Milner and McIntosh (2002).)

The main experiment was performed on a separate day following the diagnostic tests, with a median interval of 26.5 days (range 3–44 days) between the sessions (see Table 1). Despite this variable interval, the individual patients' results in the main experiment (Section 3.4) and their strong correlation with the earlier diagnostic tests (Section 3.5) confirm that our patients still had neglect at the time of the main experiment.

CT scans for all patients were interpreted by an experienced neuroradiologist (DB), blind to the results of the main experiment. Given the relevance of Milner and Goodale's (1995) model of cortical visual processing, particular attention was paid to the distinction between inferior parietal lobe (IPL) and superior parietal lobe (SPL) damage. The major anatomical findings are summarised in Table 2.

2.2. Procedure

2.2.1. Apparatus

The apparatus is illustrated in Fig. 1. Subjects were seated in front of a 60 cm^2 white stimulus board, placed flat on a table, with their right index finger at the start position. Two dark grey cylinders (24.5 cm tall and 3.5 cm in diameter) could be fixed into the board, one on either side of the midline, at a distance of 25 cm from the start position. Each cylinder could occupy one of two locations, with its inside edge 8 or 12 cm away from the midline. The factorial combination of these locations created four cylinder configurations. A 5 cm-deep strip of grey tape spanned the far edge of the board, at a depth of 20 cm behind the cylinder locations. All subjects performed the bisection task and the reaching task in separate blocks, with the order of blocks balanced

Table 1
Clinical details for the neglect patients

Patient number	Age/sex	Days post-stroke	VFD (+/−)	Line cancellation (L/R)	Star cancellation (L/R)	Line bisection (%)	Drawing (+/−)	Copying (+/−)
N1	71/F	16, 50	+	100/67	100/70	83.58	+	+
N2	71/M	14, 34	+	0/0	100/44	25.69	−	+
N3	74/M	40, 67	−	0/0	67/4	88.78	+	+
N4	76/M	134, 178	+	6/0	22/7	30.24	+	+
N5	63/M	45, 82	+	100/11	100/44	75.44	+	+
N6	65/M	15, 18	+	100/56	100/59	74.47	+	+
N7	74/M	10, 22	+	100/33	100/48	79.68	+	+
N8	77/F	32, 70	−	100/61	100/85	100.81*	+	+
N9	67/M	20, 35	−	6/0	41/4	21.79	−	+
N10	65/M	58, 84	+	100/44	100/63	56.26	+	+
N11	61/M	4, 31	+	100/50	100/63	83.90	+	+
N12	51/M	67, 76	+	44/0	89/26	0.32	−	+

VFD: visual field defect to confrontation. Days post-stroke: the first figure refers to the screening tests, the second to the main experiment. Line and star cancellation: % targets omitted in each half of sheet. Line bisection: mean rightward bisection error across the three 205 mm lines of the BIT, expressed as a percentage of the stimulus line half-length (*patient N8 placed her transection to the right of the entire line for the leftmost stimulus, producing a mean rightward error exceeding 100%). Drawing and copying: presence/absence of left neglect.

Table 2
CT readings for the neglect patients

Patient Number	Frontal lobe	Parietal lobe		Temporal lobe	Occipital lobe	Basal ganglia	Internal capsule
		SPL	IPL				
N1	Post–inf	−	+	Ant–sup	−	Lent–caud	Ant
N2	+	−	−	Ant–sup	−	Caud	Ant
N3	Post–inf	+	+	Ant–sup	−	−	Post
N4	−	−	Post	−	−	Lent	Genu–post
N5	−	−	−	−	−	Lent–caud	Ant–genu–post
N6	Post	Ant	Ant	−	−	Caud	Genu–post
N7	−	−	−	+	−	−	Genu–post
N8	post	Ant	Ant	Ant–sup	−	Lent–caud	Ant–genu–post
N9	Post–inf	−	Ant	Ant–sup	−	Lent–caud	Ant
N10	−	−	+	Post	Ant–sup	−	Post
N11	Post–inf	−	+	−	+	−	−
N12	Post	+	+	−	−	Lent	Genu

A '+' sign indicates extensive damage. More circumscribed damage is described using the following abbreviations: ant (anterior); post (posterior); inf (inferior); sup (superior); lent (lentiform nucleus); caud (caudate nucleus).

across subjects within each group. Responses were recorded by sampling the position of a marker, attached to the nail of the right index finger, at a frequency of 86.1 Hz using an electro-magnetic motion analysis system (*Minibird*, Ascension Technology Inc.).

2.2.2. Bisection task

The subject was told that this was a test of "accuracy of judgement" and that their objective was to place their right index finger exactly midway between the two cylinders. On every trial, a strip of white card was placed between the

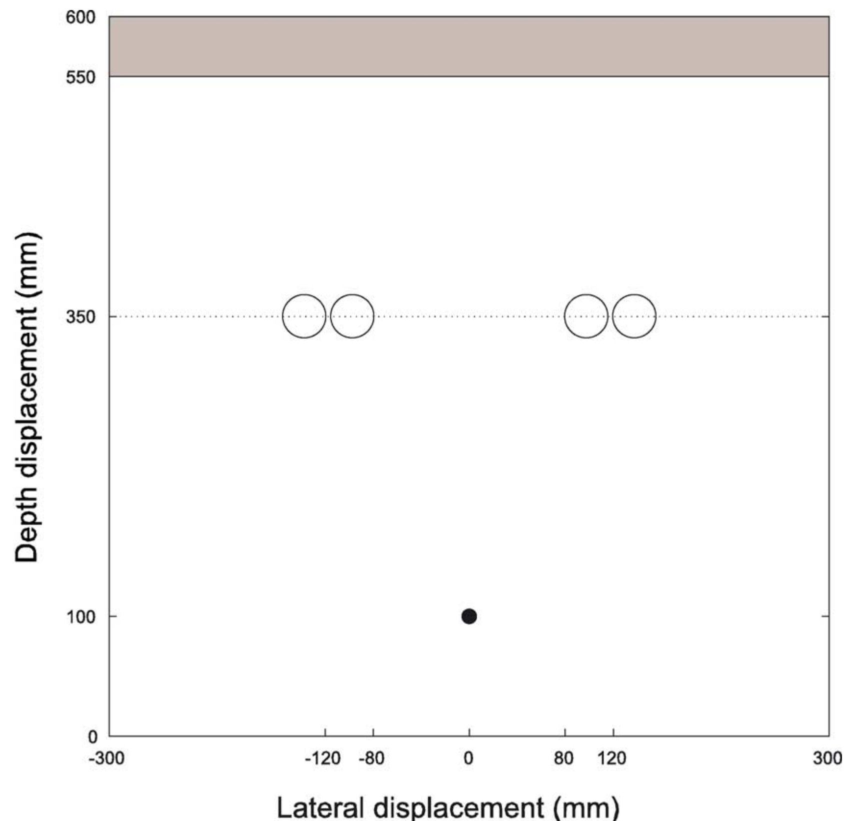

Fig. 1. Plan view of the apparatus used in the experiment. Cylinders were always presented in pairs, one on either side of the midline. The open circles show their possible locations, with inside edges 8 and 12 cm from the midline. All trials began with the subject's right index finger resting on the start position (black dot). The bisection task required the subject to place their index finger midway between the two cylinders. The reaching task required the subject to reach out and touch the target zone (grey strip) with their index finger, as rapidly as possible.

cylinders to prevent the subject from using any visible holes in the board to aid their judgement. They were informed that the positions of the cylinders would vary from trial to trial, but that there would always be one on the left and one on the right. Each trial began with the subject's index finger on the start position. The cylinders were placed in position, and the subject moved their index finger to where they judged the midpoint of the gap between the cylinders to be. No time restrictions were imposed on the response. As soon as the subject indicated that they were satisfied with their judgement, the position of the finger marker was recorded for one second. The dependent measure on each trial was the average lateral position (P) of the finger marker, with respect to the midline of the stimulus board, during this 1 s period. Each subject made 48 bisection responses, 12 for each of the four cylinder configurations, in a fixed pseudo-random order.

2.2.3. Reaching task

The subject was told that this was a test of "speed of movement" and that their objective was to reach out and touch any point on the grey strip, with their right index finger, as rapidly as possible following a verbal "go" signal. They were informed that, whenever a cylinder was present, there would be one on the left and one on the right, and that they should pass their hand between the two cylinders, rather than around the outside edge of the board. Following these initial instructions, the cylinders were not mentioned during the rest of the experiment. Each trial began with the subject's index finger on the start position. The cylinders were placed in position, and the experimenter gave the go signal. Each reaching movement was recorded in full. The dependent measure was the lateral position (P) of the finger marker, with respect to the midline of the stimulus board, as it crossed the virtual line joining the two cylinder locations (the exact value of P was estimated by linear interpolation). Each subject made 60 reaches in a fixed pseudo-random order, with 12 trials for each of the four cylinder configurations, and 12 trials in which no cylinder was present. The 12 trials with no cylinder in place were included to check for any systematic spatial biases when the reaching response was not constrained by potential obstacles.

2.3. Analysis

A preliminary analysis was performed on those reaching trials in which no cylinder was present, to check for differences between the groups when making an unconstrained reach to the grey target strip. An independent *t*-test, corrected for unequal variances, found no mean difference between the groups [$t(13) = 0.60$, $P = 0.56$], with both groups passing on average close to the board midline (control mean $P = -7.0$ mm, S.D. 8.5; neglect mean –1.9 mm, S.D. 28.5). These no-cylinder trials were excluded from subsequent analyses.

The main analysis was a repeated-measures ANOVA of response position P, with task (bisection, reaching), left cylinder location (near, far) and right cylinder location (near, far) as within-subjects factors, and group (control, neglect) as a between-subjects factor. It should be emphasised that the dependent variable P coded the lateral position of each response with respect to the centre of the stimulus board (i.e. a fixed reference frame) rather than with respect to the centre of the gap between the two cylinders presented on that trial. This measure is importantly different from the more traditional measure of directional bisection error. As noted in the Introduction, the purpose of this experiment was not to examine bisection behaviour per se; indeed the reaching task was not a true bisection task at all. Rather, the conceptual correspondence between the tasks is that both require a spatial response that depends simultaneously on the location of objects (cylinders) on either side of space. Theoretical interest thus focuses on the respective influences of the left and right cylinders upon P. Nonetheless, since the four cylinder configurations presented were symmetrical around the centre of the stimulus board, the mean value of P in each task is equivalent to the mean directional bisection error for that task.

3. Results

3.1. Main analysis

Fig. 2 shows the group mean responses for each cylinder configuration in each task. There was a significant main effect of task [$F(1, 22) = 150.36$, $P < 0.0005$]. This primarily reflected an overall leftward bias in the reaching responses that was not present in the bisection responses. Given the magnitude of this leftward bias (16.7 and 19.2 mm in the control and neglect groups, respectively), it seems likely to be a simple artefact of the placement of the marker on the right index finger, which lies to the left of the centre of the hand in its palm-down reaching posture. The bisection responses were unaffected by this bias because the subjects were asked specifically to use the index finger when making these responses. Of greater potential interest was the significant interaction of task by group [$F(1, 22) = 4.63$, $P < 0.05$]. The neglect group responded slightly further leftwards than controls in the reaching task and slightly further rightwards in the bisection task (Fig. 2). However, follow-up ANOVAs failed to uphold significant differences between groups within either task (see below).

Both cylinders had a pronounced influence on P, with highly significant effects of left cylinder location [$F(1, 22) = 189.63$, $P < 0.0005$] and right cylinder location [$F(1, 22) = 307.04$, $P < 0.0005$]. The effect of the right cylinder was involved in a two-way interaction with the factor of task [$F(1, 22) = 13.01$, $P < 0.005$] and a three-way interaction with task and subject group [$F(1, 22) = 4.96$, $P < 0.05$]. For the left cylinder, the main effect was involved in a two-way interaction with subject group [$F(1, 22) = 18.55$, $P < 0.0005$] and a three-way interaction

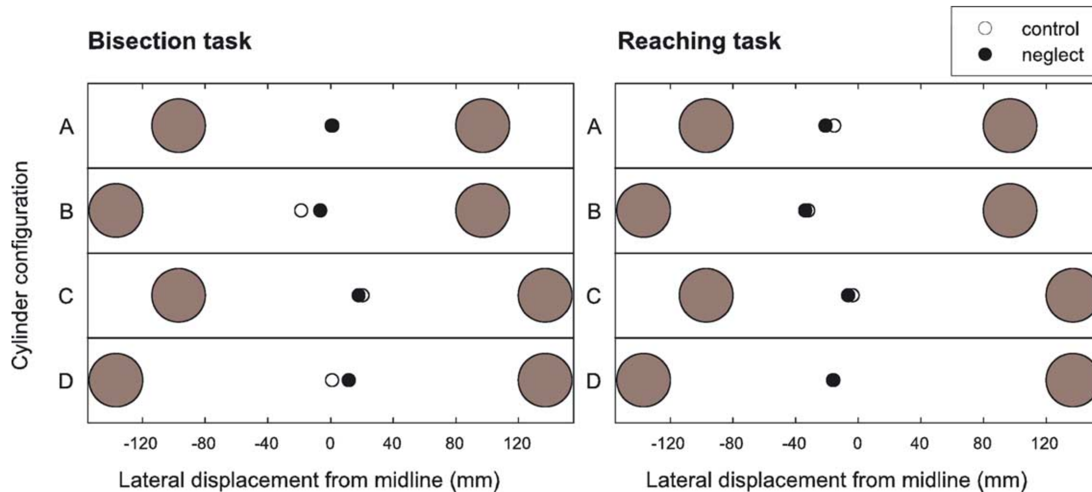

Fig. 2. Mean lateral response positions (P) in the bisection task and the reaching task. The large grey circles depict the stimulus cylinders.

with group and task [$F(1, 22) = 16.65$, $P < 0.0005$]. This latter interaction reflects the fact that the neglect patients were particularly insensitive to the left cylinder location when performing the bisection task. In Fig. 2, this effect is seen in the conspicuous differences between the groups for stimulus configurations B and D of the bisection task. The control subjects moved their transection point appropriately (by about 20 mm) as the left cylinder was shifted (by 40 mm) between the near and the far locations, but the neglect patients were much less sensitive to this shift.

Given its theoretical importance, this interaction was explored further by conducting ANOVAs by group (control, neglect), left cylinder location (near, far) and right cylinder location (near, far) for each task separately. Additionally, as an aid to visualisation, the data from Fig. 2 have been re-plotted in Fig. 3 to show the mean change in P that was associated with a shift of the left cylinder or of the right cylinder between its two locations (i.e. how much the response shifts as a function of a 40 mm shift of one or the other cylinder). These values (dP_L and dP_R) can be considered to reflect the "weightings" given to the left and right cylinder locations, respectively, in determining the responses of each group in each task. They were calculated according to the following equations:

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

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

3.2. Bisection task

For the bisection task, the factor of subject group failed to reach significance [$F(1, 22) = 1.31$, $P = 0.27$]. Therefore, although the neglect patients bisected further rightwards than controls on average (Fig. 2, left), this was not reliable. However, the lack of an overall bisection bias does not imply that the neglect group's behaviour was unbiased in terms of its dependence of the locations of the left and the right cylinders. The main effects of left cylinder location [$F(1, 22) = 238.02$, $P < 0.0005$] and right cylinder location [$F(1, 22) = 394.47$, $P < 0.0005$] were robust, but

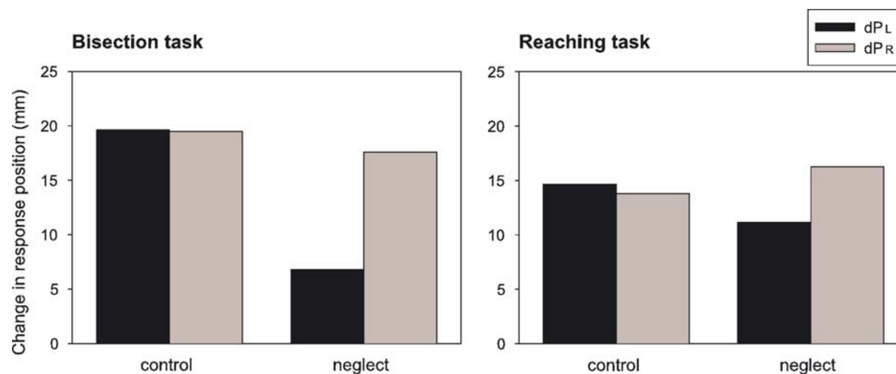

Fig. 3. The mean change in lateral response position (P) induced by a 40 mm shift in the location of the left cylinder (dP_L) or the right cylinder (dP_R) in each task.

a significant interaction of left cylinder location by subject group [$F(1, 22) = 56.09$, $P < 0.0005$] confirmed that the bisection responses of neglect patients were less affected by the location of the left cylinder than were the responses of the control subjects. The reduced weighting for the left cylinder amongst neglect patients performing the bisection task is illustrated clearly in Fig. 3 (left).

3.3. Reaching task

Fig. 2 shows that, overall, the two groups performed in a similar fashion on the reaching task. The analysis found no significant effect of subject group [$F(1, 22) = 0.38$, $P = 0.54$], and the effects of left cylinder location [$F(1, 22) = 96.91$, $P < 0.0005$] and right cylinder location [$F(1, 22) = 156.70$, $P < 0.0005$] did not interact with subject group. By contrast with the asymmetrical effects seen in the bisection task, the neglect patients and the controls shifted their movement trajectories approximately equally when either cylinder was moved between its near and far locations. In Fig. 3 (right), this is reflected in the relatively similar values of dP_R and dP_L for both groups, indicating that the spatial path of the reach was determined to a comparable extent by the locations of the two cylinders.

3.4. Individual variation

The reaching responses of both groups were sensitive to the locations of both cylinders, but the bisection responses of the neglect group were peculiarly insensitive to the location of the cylinder on the left. Nonetheless, even in the reaching task there was a qualitative trend toward a reduced influence of the left cylinder relative to the right cylinder (Fig. 3, right). Fig. 4 reveals that this trend was driven very substantially by the behaviour of two patients within the neglect group. For each subject, the difference between the weightings associated with the right and left cylinders ($dP_R - dP_L$) has been calculated separately for the reaching and bisection tasks, and these “asymmetry indices” have been co-plotted as a scattergram. An asymmetry index of zero represents symmetrical influences of the left and right cylinders on response position P, with negative values reflecting a greater influence of the left cylinder and positive values reflecting a greater influence of the right. Note that, in Fig. 4, distinct symbols have been used to represent those neglect patients that had direct damage to the SPL, and those that did not.

Without exception, the neglect patients showed a positive asymmetry index in the bisection task, being less influenced by the left cylinder location than by the right cylinder location. There was no overlap between the bisection asymmetry indices of neglect patients and control subjects, indicating that all patients showed perceptual neglect at the time of testing. In the reaching task, by contrast, there was considerable overlap between patients and controls. The majority of neglect patients conformed to the dissociated pattern of performance identified by the group analysis. However, the

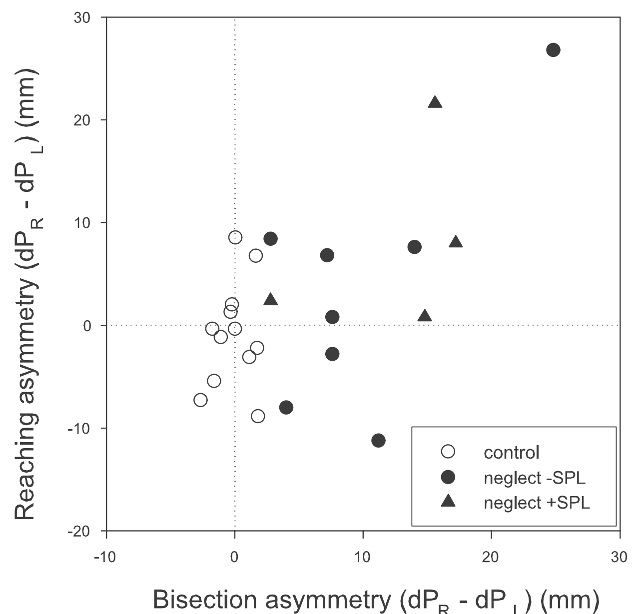

Fig. 4. Scatterplot of the asymmetries in the influence of the two cylinders ($dP_R - dP_L$) for the bisection task and the reaching task. Note that distinct symbols have been used for those neglect patients that had direct damage to the SPL (neglect + SPL), and those that did not (neglect − SPL).

two patients in the upper right portion of Fig. 4 were notable exceptions to this rule. These patients (N1 and N8 in Table 1) had strongly positive asymmetry indices in both tasks, paying more attention to the right than to the left cylinder whether reaching between them or bisecting the gap. In these two patients, at least, the group dissociation between neglect for the reaching and bisection tasks was not observed. Although one of these anomalous patients had direct damage to the SPL, the presence of SPL damage did not bear any clear relationship overall to the degree of neglect exhibited in the reaching task.

3.5. Relationships between the variables

The prevailing dissociation between attentional allocation in the bisection and the reaching tasks implies that a patient’s asymmetry index in one task should not depend upon their asymmetry index in the other. For the present cohort, this issue is complicated by the fact that at least two patients did not conform to the dissociation observed at the group level (Fig. 4). However, for the remaining patients, the asymmetry indices are clearly independent, which is consistent with a dissociation between the expression of neglect on the two tasks.

It is also worth considering the relationship between our asymmetry index on the gap bisection task ($dP_R - dP_L$), and the more traditional measure of neglect offered by directional bisection error. These alternative measures of bisection behaviour have been co-plotted in Fig. 5 for all subjects. The unifying feature of neglect performance was that

Table 3
Spearman's correlations for two alternative measures of gap bisection performance, and prior performance on target cancellation and line bisection tasks, for the 12 neglect patients

	Gap bisection error	Gap bisection asymmetry index	Cancellation index	Line bisection error
Gap bisection error		0.57	0.13	0.23
Gap bisection asymmetry index	0.57		0.71*	0.76**
Cancellation index	0.13	0.71*		0.57
Line bisection error	0.23	0.76**	0.57	

The cancellation index is the percentage of targets omitted across line crossing and star cancellation; the line bisection error is averaged across the three lines presented. Due to the non-normality of the line bisection errors, we used Spearman's correlation coefficient for ranked data, which minimises the influence of extreme values.

* $P < 0.05$.

** $P < 0.01$.

the asymmetry indices were all positive, even for patients who made mean bisection errors that were leftward or zero. This suggests that the asymmetry index provides a more valid measure of neglect behaviour on this task than does mean directional error. This conclusion is bolstered by the fact that the asymmetry index on the bisection task proved to be a better predictor of prior performance on the neglect screening tasks. Table 3 shows the correlations between the alternative measures of neglect on the gap bisection task and performance of the neglect screening tasks (target cancellation and line bisection). In evaluating Table 3, it should be recalled that the neglect screening tasks were administered at a variable interval before the main experiment (see Table 1), which makes it difficult to generalise from the absolute magnitudes of the correlations. Nonetheless, the superior predictive power of the asymmetry index over directional bisection error is plainly evident. In fact, the correlations between the asymmetry index and the neglect screening tasks are stronger than the correlations between target cancellation and line bisection tasks, despite the fact that the latter two tasks were performed in a single session.

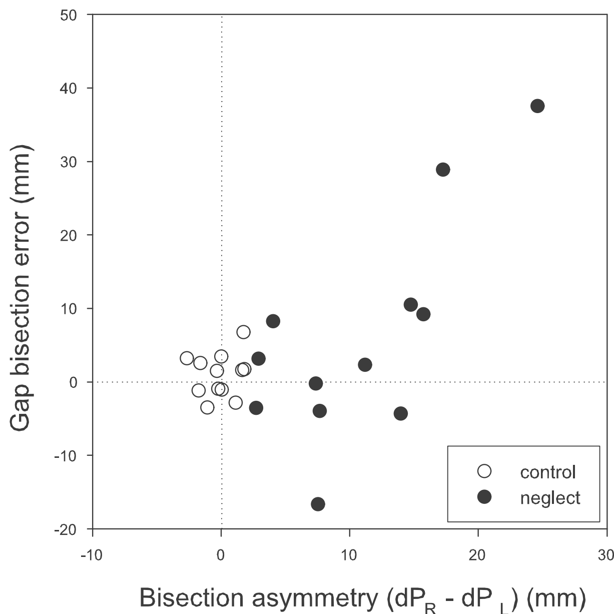

Fig. 5. Scatterplot of two alternative measures of neglect behaviour in the gap bisection task—bisection asymmetry index and directional bisection error.

4. Discussion

We asked patients with left visual neglect to bisect the gap between two cylinders or to reach rapidly between them to a more distal target zone. Our analysis focused upon the relative influence of the left and right cylinders on the location of the response. The results obtained in the bisection task indicate that this analysis may be more sensitive to neglect than are traditional measures of directional bisection error. Thus, although almost all of our patients had previously shown pathological rightward errors on a diagnostic line bisection task, they did not deviate significantly rightward as a group in bisecting the gap between the cylinders: five patients even made mean leftward errors. This supports prior demonstrations of a reduction of rightward bisection error for gap stimuli (Bisiach, Pizzamiglio, Nico, & Antonucci, 1996; McIntosh, McClements, Dijkerman, & Milner, in press). The high degree of individual variation is also consistent with observations that the presentation of gap stimuli may have different consequences in different patients (Bisiach, Rusconi, Peretti, & Vallar, 1994; McIntosh, McClements, Dijkerman, et al., in press) and that manipulations that reduce rightward bisection errors in neglect can also reverse these errors in some cases (e.g. Mattingley, Pierson, Bradshaw, Phillips, & Bradshaw, 1993; Bisiach et al., 1994). However, despite this individual variation in gap bisection error, all neglect patients showed a similar asymmetry of influence of the two cylinders, with the left cylinder exerting less influence than the right. Moreover, when this asymmetry was quantified for each patient, the resulting index of performance was found to correlate extremely well with prior performance on neglect screening tasks.

In contrast to their performance on the bisection task, the neglect group took near-normal account of the locations of both cylinders when reaching between them. Evidently, the extent to which left neglect patients can attend to objects

on the left side of space, in the presence of competing stimulation from the right, depends upon the nature of the task that they perform. Fast reaching responses may facilitate a more even distribution of attention than is possible when making an explicit bisection judgement. This overall outcome is reminiscent of the findings of Robertson et al. (1995), and likewise supports Milner and Goodale's (1995) prediction that the perceptual symptoms of visual neglect should not impair the visuospatial computations underlying the guidance of action. Our analysis of individual performances, however, revealed clear exceptions to this rule. Two patients (N1 and N8) showed strong neglect in both the bisection and the reaching task. Thus, our preliminary conclusions (Milner and McIntosh, 2002), reached before the full cohort of patients was tested, must now be moderated. The predicted sparing of visuomotor functions does not apply to all neglect patients, although it still seems to apply to most. Obviously, therefore, it is of interest to ask what distinguishes those neglect patients with preserved visuomotor guidance from those without.

Milner and Goodale (1995) and Milner (1995) argued that there may be separate neural modulation processes for "visuomotor attention" and "perceptual attention" operating in the dorsal and ventral streams respectively, with the dorsal attentional system in control overall. Recent functional MRI studies provide support for this notion of a superior parietal system in control of visuospatial attention, providing top-down modulation of activity in inferior parietal and occipito-temporal areas (Corbetta, Kincade, Ollinger, McAvoy, & Schulman, 2000; Hopfinger, Buonocore, & Mangun, 2000; Kastner & Ungerleider, 2001; Yantis et al., 2002). This scheme would predict a close coupling between perceptual and visuomotor attention in healthy subjects, as has been found in several behavioural studies (e.g. Schneider & Deubel, 2002). However, it would also predict that damage "downstream" from the superior parietal region could impair perceptual attention without disrupting visuomotor attention, whereas damage to the superior region itself should have deleterious consequences for both kinds of visual attention. Accordingly, we would predict that patients, like N1 and N8, who show a pathological bias in both our bisection and reaching tasks, should have brain damage directly or indirectly affecting the SPL. Similarly, the apparent preservation of visuomotor attention in the majority of our patients should indicate that the SPL is functionally intact.

The anatomical data presented in Table 2, however, fail to give clear support to these predictions. Although patient N8 did indeed have damage to the SPL, the same region was damaged in three patients who showed normal obstacle avoidance (N3, N6 and N12). Conversely, patient N1 was impaired on the reaching task although her lesion did not involve the SPL directly. As such, the CT data indicate that SPL damage is neither necessary nor sufficient to induce neglect of left-sided obstacles on our reaching task. Indeed, Table 2 provides no unique anatomical correlate for the behavioural pattern exhibited by patients N1 and N8. This is perhaps unsurprising, given the fact that only gross structural damage, rather than its functional consequences, could be detected. Moreover, it is possible that, like many other symptoms of neglect, a failure to attend to obstacles on the left side during reaching can have more than one possible cause. It is worth noting, however, that although the present evidence suggests that obstacle avoidance can survive partial damage to the SPL, we have recently found that it is severely compromised when the damage is sufficient to cause optic ataxia (Rice, Schindler, Rossetti, & Milner, 2003).

One obvious limitation of the present study is that perceptual and visuomotor biases were assessed by separate tasks, rather than by separate measures of performance within a single task. This raises the possibility that differences in performance between the tasks might be due to some factor correlated with but not intrinsic to the type of response required. For instance, patients may have made more of an effort to pay attention to the left cylinder in the reaching task because the potential cost of not doing so was an undesirable collision. Alternatively, the instruction to move as fast as possible in the reaching task may have had the effect of increasing the patients' level of arousal, thereby reducing their tendency to neglect (Robertson, Mattingley, Rorden, & Driver, 1998). Moreover, since no measure of awareness was collected in either task, we cannot know for certain whether the increased influence of the left cylinder on neglect patients in the reaching task was associated with an enhanced perceptual awareness of its location or was indeed implicit as we have assumed. However, we have recently tested a patient with visual extinction on a closely related task. This patient skilfully avoided obstacles on both sides of space, regardless of whether he could report the presence of the left one verbally (McIntosh, McClements, Schindler, et al., 2004; Milner & McIntosh, 2003). This direct demonstration that obstacle avoidance can proceed implicitly under conditions of pathological inattention provides considerable circumstantial support for a similar interpretation of our neglect patients' behaviour.

In apparent contrast to our observation of preserved obstacle avoidance in neglect patients, there is a common wisdom that patients with neglect routinely collide with objects, such as door frames and furniture, on the neglected side when navigating on foot (or in a wheelchair). In fact, very little research has been directed at everyday "bumping" in neglect patients, so it is difficult to judge how discrepant these observations are from the level of neglect observed in our reaching task. Nonetheless, our reaching task was not intended as a tabletop model of whole-body navigation, and the demands facing the subjects were very different. The task was performed entirely within near (reaching and grasping) space, with the obstacles present throughout, and the response was a single smooth movement. Successful locomotion, by contrast, implies the advance planning of routes around obstacles in far (walking and throwing) space, which may not pose a threat to the sub-movement presently being

executed. Such advance planning may be especially vital considering that the obstacle may no longer be in view at the crucial moment; a low chair may lie below the current field of view, or a door frame behind the line of sight. A further critical factor for successful locomotion is an accurate representation of one's own body, and its current position, which may be lacking in patients with neglect (Bisiach, Perani, Vallar, & Berti, 1986). These considerations suggest that the parallels between the present reaching task and everyday locomotion may be rather limited. We would note that it is not commonly observed that patients with neglect collide with one object when reaching for another, which would be more directly analogous to our visuomotor task.

The behavioural findings of the present study are compatible with Milner and Goodale's (1995) view of neglect as primarily a perceptual disorder. The occurrence of neglect in our reaching task in two patients does not detract from the dissociation seen in most of our patients. A more serious challenge for Milner and Goodale's view comes from the recent demonstration by Marotta et al. (2003) that patients with neglect select more rightward (and less stable) grasp points than do normal subjects when picking up irregularly shaped objects. This bias was present in all six of the patients tested by Marotta et al. and was found to correlate significantly with neglect on conventional sub-tests of the BIT. The discrepancy between these findings and the present report of preserved visuomotor guidance in a majority of neglect patients implies that not all visuomotor tasks are equivalent. That is, whilst Milner and Goodale's (1995) hypothesis has predictive power for some aspects of visuomotor processing in neglect (Robertson et al., 1995; Pritchard et al., 1997; Edwards & Humphreys, 1999), it may not hold for others (Marotta et al., 2003). The empirical challenge now is to determine which visuomotor abilities are typically spared in neglect and which are not, and to seek specific anatomical correlates for these patterns of association and dissociation. The signature rightward bias of neglect may offer a valuable behavioural marker by which to investigate the detailed organisation of perceptual and motor systems in the human brain.

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