Exp Brain Res (2003) 153:220–230
DOI 10.1007/s00221-003-1595-1

RESEARCH ARTICLE

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Ocular scanning and perceptual size distortion in hemispatial neglect: effects of prism adaptation and sequential stimulus presentation

Published online: 4 September 2003

Abstract When asked to compare two lateralized shapes for horizontal size, neglect patients often indicate the left stimulus to be smaller. Gainotti and Tiacci (1971) hypothesized that this phenomenon might be related to a rightward bias in the patients' gaze. This study aimed to assess the relation between this size underestimation and oculomotor asymmetries. Eye movements were recorded while three neglect patients judged the horizontal extent of two rectangles. Two experimental manipulations were performed to increase the likelihood of symmetrical scanning of the stimulus display. The first manipulation entailed a sequential, rather than simultaneous presentation of the two rectangles. The second required adaptation to rightward displacing prisms, which is known to reduce many manifestations of neglect. All patients consistently underestimated the left rectangle, but the pattern of verbal responses and eye movements suggested different underlying causes. These include a distortion of space perception without ocular asymmetry, a failure to view the full leftward extent of the left stimulus, and a high-level response bias. Sequential presentation of the rectangles and prism adaptation reduced ocular asymmetries without affecting size underestimation. Overall, the results suggest that leftward size underestimation in neglect can arise for a number of different reasons. Incomplete leftward scanning may perhaps be sufficient to induce perceptual size distortion, but it is not a necessary prerequisite.

Keywords Neglect · Visual perception · Eye movements · Prism adaptation · Size distortion

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Introduction

A common symptom of hemispatial neglect following right hemisphere lesions is that, when asked to bisect a line, patients place their mark too far to the right. Previous investigations have focused on whether this ipsilesional deviation is due mainly to motor difficulties in making a leftward response, or to a perceptual misrepresentation of space (Heilman and Valenstein 1979; Bisiach et al. 1990, 1998; Coslett et al. 1990; Milner et al. 1993). These studies have generally implicated perceptual more than motor factors, and it has been suggested that the neglected parts of perceptual space might be relatively compressed (Milner 1987). Evidence for this comes from visual size matching studies in which two stimuli (usually horizontal lines or rectangles) are presented side by side and the patient is asked to judge which is larger or smaller. Neglect patients often judge the left stimulus to be smaller when they are of equal size, or even when the leftward stimulus is larger (e.g. Milner and Harvey 1995; Irving-Bell et al. 1999). Recent investigations have found that this leftward size underestimation is especially present when neglect patients additionally have a visual field defect (Doricchi and Angelelli 1999). Furthermore, pronounced size underestimation can occur in patients with hemianopia but without clinical signs of neglect (Ferber and Karnath 2001). The current study aims to investigate further several aspects of perceptual size matching. The first question to be addressed is the role of eye movements.

Size underestimation in neglect was first observed by Gainotti and Tiacci (1971), in a study of visual perception. They reported that visual neglect was strongly associated with a tendency to judge the rightward partner in a pair of geometrical figures as larger. Also noted was a tendency of neglect patients to fix their gaze mostly on the rightward figure. Making an explicit link between these observations, the authors proposed that "this asymmetry of visual perception is due to the asymmetrical exploration of space shown by patients with unilateral spatial neglect... the space of visual perception is not homogeneous, but the elements on which gaze is mostly fixed are systematically overvalued" (Gainotti and Tiacci 1971, p. 456). Such biased visual exploration is readily confirmed by informal observations, and experimental investigations have now described the abnormalities more formally. They include a reduction in the time spent looking left of centre, an ipsilesional shift of the distribution of fixations (Ishiai et al. 1987, 1992; Hornak 1992; Karnath and Fetter 1995; Barton et al. 1998) and a tendency to saccade initially rightwards when presented with bilateral stimulation (Walker and Findlay 1996). Clearly, such biases could have a powerful influence on the performance of neglect patients across a range of tasks, including size matching.

Gainotti and Tiacci argued that rightward elements are overvalued because the patients spend a greater proportion of the available time looking at them. However, there may be an additional reason. Spatial asymmetries in the extent of visual exploration might mean that, in some cases, neglect patients do not even see the entirety of the leftward stimulus. Moreover, as most patients with leftward size underestimation also have a left visual field defect (Doricchi and Angelelli 1999; Ferber and Karnath 2001), a failure to look fully to the left could result in the left stimulus never falling entirely in the intact visual field. The initial aim of the present study was simply to document the scanning patterns of patients with neglect during performance of horizontal size-matching tasks. The intention was to observe whether asymmetries of oculomotor behaviour are a necessary accompaniment of size underestimation. In addition, eye movements were manipulated experimentally by using sequential presentation of the two stimuli (as well as the usual simultaneous procedure), in order to increase the likelihood of symmetrical visual exploration.

It should be noted that such sequential presentation also alters the size-matching task in other significant ways. It introduces a memory requirement, and also removes the element of simultaneous attentional competition (Kerkhoff 2000; Riestra et al. 2001). Kerkhoff found that leftward size underestimation was significantly reduced when pairs of stimuli were presented sequentially. This was taken to indicate an important role for attentional competition in the size underestimation phenomenon. Our reasons for employing a sequential matching procedure are quite compatible with Kerkhoff's. Reduced attentional competition would be expected to be accompanied by an increased symmetry of visual exploration in neglect, and both may be associated with reduced size underestimation.

A second aim of the current study was to assess the influence of prism adaptation on size underestimation and ocular scanning. Rossetti et al. (1998) observed that after adaptation to base-left wedge prisms, which produce a rightward deviation of the visual field, the performance of neglect patients on several standard screening tasks improved dramatically. The effect of prism adaptation was not restricted to those symptoms that rely on visuo-proprioceptive mapping (such as pointing straight ahead). Symptoms such as rightward errors in line bisection, left omissions in cancellation tasks and failure to copy the left half of a line drawing were also reduced (Rode et al. 1998, 2001; Frassinetti et al. 2002; Farnè et al. 2002; McIntosh et al. 2002). The effects of prism adaptation on perceptual size matching and on ocular scanning are of interest in their own right. Additionally, this manipulation was intended to provide a second means to assess the relation between eye movements and perceptual size judgements. Of course, if prism adaptation is found to restore the symmetry of both oculomotor scanning and perceptual size judgements, then this result would not identify the root cause of the change. However, any clear *dissociations* observed between the effects of adaptation on scanning patterns and on perceptual judgements would be informative. A previous example of such a dissociation is provided by the differential effect of prism adaptation on bisection and straight ahead judgements (Pisella et al. 2002). In particular, if symmetrical visual search could be achieved without improving the symmetry of size perception, this would disprove the idea that the size underestimation phenomenon is causally dependent on oculomotor deficits.

Materials and methods

Subjects

Three visual neglect patients (R.D., C.S. and G.M.) participated in the study. In each case, visual neglect was observed on at least two of three standard diagnostic tasks administered prior to prism adaptation (see later).

R.D.: a 50-year-old right-handed man who suffered a subarachnoid haemorrhage, which bled into the right sylvian fissure. A day later, he underwent surgery to have the bleed evacuated, and the internal carotid artery was clipped. A CT examination, performed 6 days later, showed a large deep infarct affecting the right cerebral peduncle, insula, basal ganglia, and deep white matter lateral to the thalamus. R.D. showed left hemianopia to confrontation. Humphrey perimetry was performed at 3 months post-stroke and confirmed that the hemianopia was homonymous and complete. R.D. also exhibited left upper and lower motor weakness.

C.S.: a 73-year-old right-handed woman who suffered a hemorrhagic stroke in the territory of the right middle cerebral artery. An MRI examination performed at 2 days post-stroke showed a large lesion in the right parietal lobe extending to postero-lateral occipital cortex, with sparing of medial occipital cortex. C.S. showed left hemianopia to confrontation. Humphrey perimetry was performed at 14 months post-stroke and confirmed that the hemianopia was homonymous and complete. C.S. had motor weakness in the left upper limb.

G.M.: a 53-year-old man who suffered an ischaemic infarct due to occlusion of a posterior branch of the right middle cerebral artery. A CT examination, performed at 5 days post-stroke, revealed a posterior parietal infarct, mainly inferior, extending to about 2.5 cm short of the midline, with sparing of the posterior cerebral territory. Several areas of low attenuation were visible in the white matter of the right hemisphere, in particular lateral to and above the frontal horn of the lateral ventricle, and in the internal capsule. G.M.'s visual fields were assessed independently by two neurologists by confrontation. Both concluded that G.M. had full visual fields. Assessment of visual extinction proved inconclusive due to a high proportion of missed unilateral stimuli on the left, but some tactile extinction was evident. G.M. also had a dense left hemiparesis.

Five age-matched right-handed control subjects (three male and two female) also participated (mean age = 60.2 years, SD = 7.2). The study was part of an ongoing research programme for which ethical approval had been granted by the Tayside Committee on Medical Research Ethics.

Overall procedure

Each patient took part in three testing sessions, two prior to prism adaptation and one afterwards. The protocol for each session is shown in Table 1:

Table 1 The experimental protocol for each of the three sessions

Session 1	Session 2	Session 3
Size-matching	Neglect screening	Prism adaptation
	Size-matching	Neglect screening (early post-test: approximately 1 h after adaptation)
		Size-matching
		Neglect screening (late post-test: approximately 2 h after adaptation)

The three sessions were performed on the following days for each patient:

R.D.: 40, 45 and 46 days post-stroke
C.S.: 360, 366 and 367 days post-stroke
G.M.: 87, 91 and 92 days post-stroke

Control subjects completed a single session during which only size matching was performed.

Neglect screening tests

Three neglect screening tasks were used: star cancellation (Wilson et al. 1987), scene copying (adapted from Gainotti et al. 1972) and line bisection. All tasks were untimed and all stimuli were presented at body midline.

Star cancellation: The A4 stimulus sheet contained 56 targets (small stars) pseudo-randomly interspersed with distracter items. The experimenter indicated clearly the full extent of the sheet and crossed out the two central targets. The patient was then asked to cancel the remaining small stars. The number of targets omitted in each lateral half of the sheet was counted. *Scene copying* required the patient to copy a simple scene made up of five items. Performance was scored in two ways: the number of items copied and the number of items symmetrically depicted. In the *line bisection* task, the patient was presented with ten black horizontal lines, each 20 cm long and 2 mm thick and each centred on an A4 sheet of white paper. Rightward errors were scored as positive values and leftward errors as negative.

Size matching task

Participants were seated in front of a 17-inch (43 cm) computer monitor (resolution 640×480 pixels). The viewing distance was 66 cm, with the centre of the screen at eye-level. The head was stabilized using a chin rest. On each trial, two black horizontal rectangles were presented on the left and right sides of the screen against a white background. Following stimulus offset, the participant was required to say which was the shorter (or longer: see below) in horizontal length. Within each test session, four blocks of trials were given. In two blocks the rectangles were presented simultaneously, and in two blocks they were presented sequentially (the first rectangle appeared on the left in 50% of the trials). To maximize detection of each rectangle in sequential trials, a verbal warning was given as to the side of the screen on which the next rectangle would appear. An ABBA design was used, starting with a block of simultaneous trials. In the first session, the neglect patients indicated which rectangle was shorter throughout the first two blocks, and which was longer throughout the last two blocks of trials. In the remaining two sessions this order was reversed. Control subjects 1, 3 and 5 indicated which of the two rectangles was shorter in the first two blocks of trials and which was longer in the third and fourth blocks. The other two control subjects responded in the reverse order.

On each trial, a standard rectangle, 8 cm long, was presented along with a comparison rectangle. The comparison rectangle was either identical to the standard or was 7.6, 7.2, 6.8 or 6.4 cm long. Each rectangle was 0.5 cm high and presented with its centre 6.0 cm to the left or right of the midline of the screen, and vertically centred on the screen. Each block of trials contained eight trials in which the left rectangle was the standard and the right was smaller (two trials for each smaller rectangle), eight trials in which the right rectangle was the standard and the left was smaller (two trials for each smaller rectangle), and eight identical-stimulus trials. Trials within a block were presented in a pseudo-random order.

Eye movements were recorded at a sampling rate of 250 Hz using the SMI *Eyelink* system. Calibration of the horizontal axis was carried out by asking the participant to fixate successively on three targets at the extreme left, extreme right, and in the centre of the screen. Calibration was performed prior to each trial block and after every eight trials within a block. Before each trial, corrections were made for signal drift by asking the participant to look at a central fixation point and 'zeroing' the output signal. The order of events for simultaneous and sequential trials is presented in Table 2. Eye position data were analysed only for the period that the rectangles were on-screen (6 s for both simultaneous and sequential displays). Central fixation was defined as the last fixation prior to stimulus onset, except when this fixation differed more than one degree from the predefined centre of the screen (320 pixels from one side) in which case a default value of 320 pixels was used as central fixation. Only horizontal eye movement data was analysed. For each trial the following dependent variables were extracted: the percentage of total fixation time spent on the left half of the screen; the leftmost and rightmost fixation points; the midpoint of the fixation range; the median location of fixations; the direction of first saccade.

Table 2 The order of events within a trial for both simultaneous and sequential stimulus presentation conditions

Simultaneous presentation	Sequential presentation
Drift correction	Drift correction
Fixation on central cross (1 s)	Fixation on central cross (2 s)
Stimulus display (6 s) (no fixation cross present)	Stimulus 1 display (3 s) (no fixation cross present)
Verbal response (blank screen)	Blank screen (1 s)
	Fixation on central cross (2 s)
	Stimulus 2 display (3 s) (no fixation cross present)
	Verbal response (blank screen)

Prism adaptation procedure

The prism adaptation procedure was an extended version of that employed by Rossetti et al. (1998). Patients wore a pair of goggles fitted with wide-field point-to-point prismatic lenses creating a rightward optical shift of 10°. Exposure consisted of 100 fast pointing movements made to visual targets presented either 10° to the left or 10° to the right of the body midline, given in pseudo-random order. A shelf was placed under the patient's chin to prevent viewing of the hand at its starting position, but allowing an unobstructed view of the targets and terminal pointing errors. This adaptation procedure took between 6–10 min. After removal of the prisms, subjects made several fast open-loop pointing movements, to allow an informal check that a prismatic after-effect was present.

Results

Neglect screening tests

The outcomes of the screening assessments are reported in Table 3. Changes in performance were tested statistically for the star cancellation (binomial test) and line bisection (one-way ANOVA). The limited number of items in scene copying task prevented formal statistical assessment. At the early post-test, all patients were improved on at least one task. At the late post-test, GM had improved on one task (but deteriorated on another task), C.S. had improved on two (and deteriorated on one), while patient R.D. had improved on all three.

Perceptual size judgements

All three neglect patients showed leftward underestimation in the size-matching task (see Fig. 1). The mean percentages of 'left is smaller' responses was more than two standard deviations above the control mean for all patients in all three sessions (see Table 4 for z-scores). Patient R.D. alone showed a consistent directional difference between presentation conditions. A binomial test showed that, across sessions, he made significantly more frequent 'left is smaller' responses in the sequential as compared with the simultaneous condition (90.7% vs. 76.4%; $p<.001$). Finally, no patient showed a reliable change in perceptual judgements following prism exposure.

In addition, we examined how the "right is smaller" responses were distributed with respect to the stimuli presented. If neglect patients tend to perceive stimuli on the left to be shorter, then we would expect a significant proportion of their "left is smaller" responses to be erroneous. However, incorrect "right is smaller" responses should occur less often. This expectation was met for patients C.S. and G.M., who identified the right stimulus as the smaller on 24% and 25% of trials overall

Table 3 Performance of neglect patients on neglect screening tasks, before and after prism adaptation. *N*+ denotes a patient with neglect and hemianopia, *N*− a patient with neglect but without hemianopia

Patient	Star cancellation % crossed out (L/R)	Scene copying (total number of number of items copied)	Scene copying (symmetry L/R)	Line bisection (mean rightward deviation from centre in mm [SD])
RD (N+)				
Pre-test	0/70	5	3/5	81.9 [1.91]
Post-test (early)	7/85*	5	5/5	86.1 [1.10]
Post-test (late)	44/85*	5	5/5	64.4 [13.4]**
CS (N+)				
Pre-test	37/100	5	1/5	53.4 [5.34]
Post-test (early)	33/96	5	1/5	42.4 [12.9]**
Post-test (late)	11/93^{+}	5	3/5	26.8 [6.21]**
GM (N−)				
Pre-test	11/93	4	2/4	13.0 [4.64]
Post-test (early)	0/85^{+}	5	5/5	16.0 [5.14]
Post-test (late)	93/81*	5	3/5	18.4 [2.95]$^{++}$

* Significant improvement with respect to pre-prism performance (binomial test, $p<0.01$)
$^{+}$ Significant deterioration with respect to pre-prism performance (binomial test, $p<0.01$)
** Significant improvement with respect to pre-prism performance (ANOVA, $p<0.05$)
$^{++}$ Significant deterioration with respect to pre-prism performance (ANOVA, $p<0.05$)

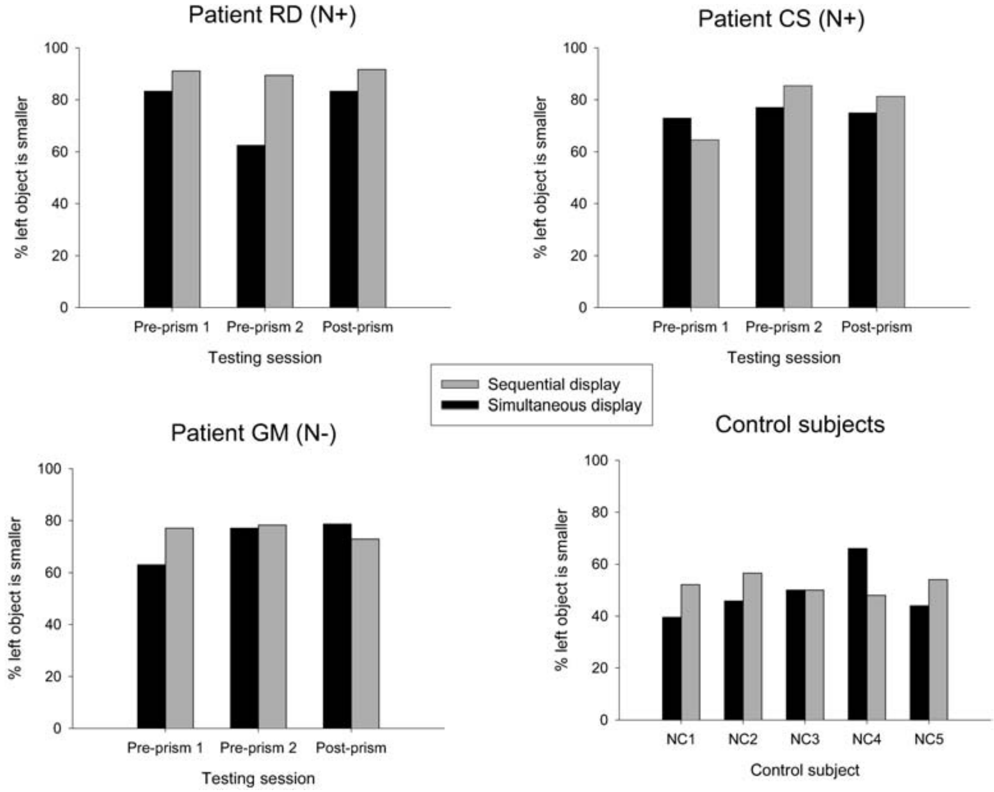

Fig. 1 The percentage of 'left rectangles is smaller' judgements (out of 48 trials) for the three neglect patients, prior to and after prism adaptation, and for the five control subjects (*bottom right*). *N*+ denotes a patient with neglect and hemianopia, *N*− a patient with neglect but no hemianopia

Table 4 Z-Scores for the main dependent variables. The data were collapsed over viewing conditions (simultaneous and sequential). *N*+ is a patient with neglect and hemianopia; *N*− is a patient with neglect but no hemianopia

	Session	Perceptual judgements (left = smaller)	Time spent looking left of midline	Leftmost fixation	Rightmost fixation	Midpoint of fixation range	Direction of first saccade
RD (N+)	1	9.12	−11.72	4.97	−.09	10.94	−9.25
	2	6.30	−9.62	4.78	.77	12.31	−9.98
	3	9.22	−4.30	2.47	.35	6.26	−9.97
CS (N+)	1	4.28	−1.04	.91	.82	.82	−8.88
	2	7.66	.33	−.58	.37	−.53	−4.53
	3	6.88	−.70	.16	−.13	.08	−6.35
GM (N−)	1	4.90	1.83	−.31	−1.34	−3.48	−6.71
	2	6.76	4.10	−.62	−1.08	−3.65	−9.97
	3	6.30	3.46	−.41	−1.39	−3.81	−5.98

respectively. For C.S., on 71% of these occasions, the right stimulus was in fact shorter than the left, with 16% of responses being made when the stimuli were equal and 13% when the left was the smaller. For patient G.M., 96% of his "right is smaller" responses were correct, with the remaining 4% being made when the stimuli were equal. By contrast, R.D. made "right is smaller" responses on 17% of trials overall, but these were utterly unrelated to the actual stimuli: 38% were made when the right stimulus was the smaller, 34% when the left was the smaller, and 28% when the two stimuli were equal.

Time spent looking left of the midline

The control subjects produced a near-symmetrical pattern of fixations overall (mean percentage of time looking left of centre = 51.3, SD = 3.11, Fig. 2). Patient C.S. spent, on average, 49.8% of time looking left of centre (for z-scores see Table 4). Patient G.M. showed a leftward biased pattern of fixation (Fig. 2), which fell within two standard deviations of the control mean only for session 1 (Table 4). A two-way ANOVA with session and condition as independent variables showed that G.M.'s temporal bias towards the left was significantly reduced in the sequential (56.7%) as compared with the simultaneous condition (65.4%; $F_{(1,282)}$=22.69, p<.001). This result is unsurprising, since fixation was externally

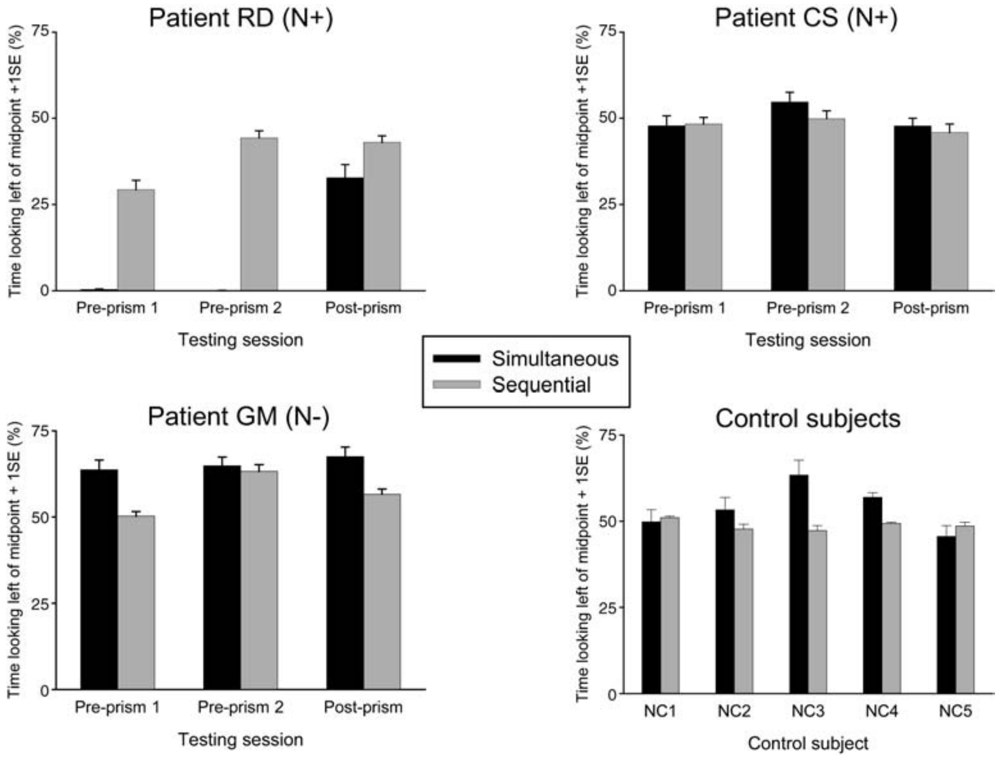

Fig. 2 The average (+SE) percentage of fixation time looking left of the central fixation cross for the three neglect patients and the control subjects. The time looking leftwards increased for patient R.D. after prism adaptation, but not for the other two patients

scheduled in the sequential condition. The ANOVA showed that no systematic change in performance was induced by prism exposure in either C.S. or G.M[1]. (see Fig. 2, Table 4).

Patient R.D. behaved rather differently, producing a strongly rightward-biased fixation pattern that was dramatically affected both by presentation condition and prism exposure. A two-way ANOVA by presentation condition and testing session found reliable effects of both factors ($F_{(1,281)}$=233.32, p<.001 and $F_{(2,281)}$=55.96, p<.001 respectively) and a reliable interaction between them ($F_{(2,281)}$=29.07, p<.001). As Fig. 2 illustrates, R.D.'s fixation pattern was closer to symmetry (though still biased rightwards) in the sequential condition and was uninfluenced by the prism adaptation treatment. By contrast, R.D. spent almost no time fixating left of the midline in the simultaneous presentation condition during either pre-prism session. Following prism exposure, a marked shift toward symmetry was observed, with the proportion of time fixating leftward in the simultaneous condition approaching that observed in the sequential condition.

Fixation range

Two alternative measures of central tendency of the spatial range of fixations were analysed. First, the median point of fixation was extracted. Second, the most eccentric leftward and rightward fixations were identified and their midpoint calculated. These measures produced closely similar results, so only the midpoint data are reported (see Fig. 3).

The fixation range data closely mirrored those for time looking left of the midline. Overall, the control group's mean range of fixations was fairly symmetrical about the midline, though biased slightly leftwards (Mean = –0.37°, SD = 0.47). Patient C.S. exhibited a mean leftward bias comparable to that of controls, and patient G.M. showed a large leftward bias (Fig. 3, Table 4). This bias was more pronounced for successive (–2.18°) than for simultaneous presentations (–1.54°), as confirmed by a two-way ANOVA, with condition and session as factors ($F_{(1,282)}$=10.5, p<.001). Neither C.S. nor G.M. showed any reliable alteration in the midpoint of fixations following prism adaptation (see also Fig. 3).

Only patient R.D. exhibited the pronounced rightward oculomotor bias that might be expected from a patient with severe visual neglect. Moreover, the midpoint of his fixation range was strongly affected by presentation condition and prism exposure. A two-way ANOVA found reliable effects of presentation condition and testing session ($F_{(1,281)}$=231.64, p<.001 and $F_{(2,281)}$=45.42, p<.001 respectively), and a reliable interaction between these factors ($F_{(2,281)}$=21.16, p<.001). As Fig. 3 shows, R.D.'s fixation range was biased rightwards in all conditions, but far more strongly in the simultaneous than in the sequential condition. The prism adaptation treatment induced no clear change during sequential

[1] There was a significant difference between sessions for G.M., with the amount of time fixating left of centre being less in session 1 as compared to the other two sessions, $F_{(2,282)}$=5.37, p<.01.

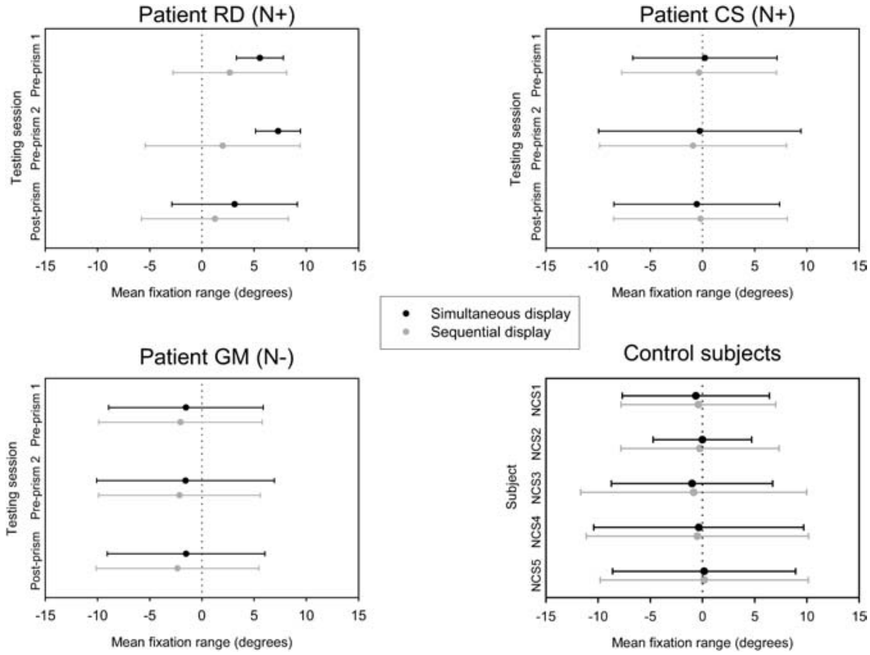

Fig. 3 The average values (for each session) of the extreme left, extreme right, and mid-point of the fixations made while viewing the rectangles, for all participants

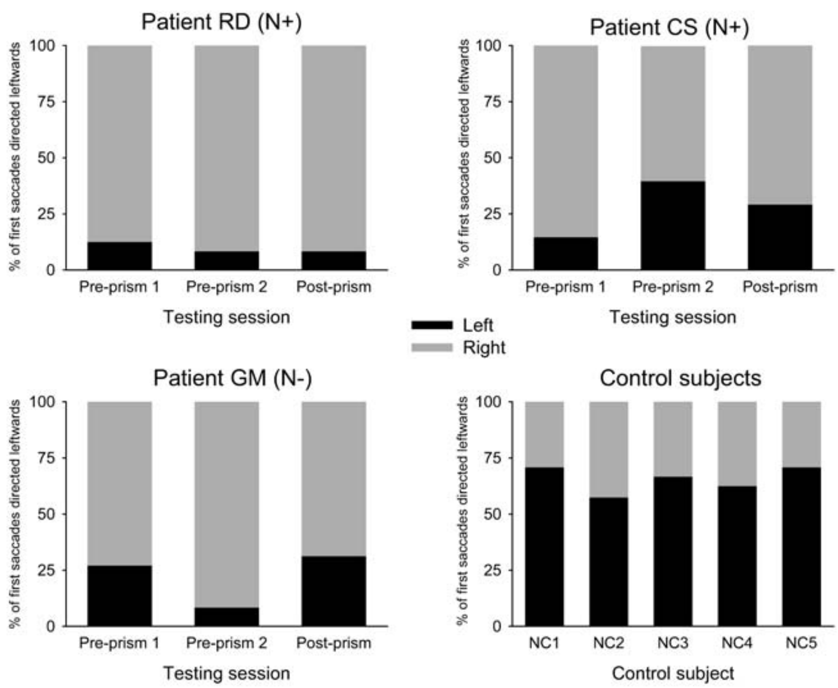

Fig. 4 The percentage of first saccades that were directed leftwards by each participant. Only data for the simultaneous display trials are depicted, since successive presentation forced participants to look first at the target that appeared first

trials, but considerably increased the leftward extent of fixation in the simultaneous trials.

Extent of leftward fixations

One possible explanation for underestimation of the horizontal extent of the left rectangle is that, due to visual field defects and incomplete scanning, only part of the rectangle was viewed by the patient. For each trial, we therefore compared the position of the left-most fixation (in screen pixels) with the position of the left edge of the left rectangle. Both R.D. and C.S. had a complete left hemianopia without macular sparing. In order to view the entire left rectangle they would have had to fixate beyond its left hand edge. R.D. achieved this in only 1.1% of trials. C.S. viewed the left edge of the target in 4.6% of trials. Thus, it is clear that neither R.D. nor CS viewed the complete left stimulus in the vast majority of trials. For both patients, the number of trials in which the entirety of both rectangles was viewed is too small to decide whether significant size underestimation was still present under these conditions.

Although none of the neglect patients scanned to the extreme left edge of the left stimulus in most of the trials, the extent of leftward scanning was well within the normal range for G.M. and C.S. (see Table 4 for z-scores). Indeed, the control subjects fixated beyond the left of the left rectangle in an average of only 3.6% of the trials. For R.D., however, leftward scanning was highly abnormal for the pre-prism simultaneous presentation trials. R.D. never fixated leftwards of the *right* hand edge of the left rectangle in any simultaneous trial prior to Session 3. It would thus have been impossible for him to view any part of the left rectangle.

Direction of first saccade

This measure is shown in Fig. 4, for the simultaneous presentation condition only (in the sequential condition, the direction of the first saccade was dictated by where the first rectangle appeared). As a group, the control subjects tended to direct the first saccade preferentially to the left side (mean percentage of first saccade left = 65.6, SD = 5.75), perhaps reflecting learned reading habits. By contrast, all three patients directed most of their first saccades to the right. Across sessions, the proportion of trials on which the first saccade was directed leftwards was only 9.71%, 27.8% and 22.2% for patients R.D., C.S. and G.M. respectively (for z-scores see Table 4). The commonality of this rightward orienting bias across the three patients contrasts with the large differences in the spatial and temporal symmetry of their ocular exploration. Prism adaptation did not modify the initial rightward orienting preference in any of the patients (see Fig. 4).

Discussion

This study aimed to investigate the relationship between underestimation of horizontal extent for objects on the neglected side, and asymmetries of ocular scanning. This link could arise because less attention is being paid to the leftward stimulus, as envisaged by Gainotti and Tiacci (1971), but also because of a simple failure see the entire left stimulus. We introduced two manipulations designed to increase the extent of leftward scanning: (i) sequential stimulus presentation and (ii) prism adaptation. Our intention was to determine whether any improvements in scanning would be accompanied by improved perceptual matching, or whether there might be dissociations. However, while the effects that were produced by these experimental manipulations were interesting, the overall patterns of behaviour of our patients provided some instructive surprises, and these will be discussed first.

Eye movements and size distortion

All three neglect patients showed comparable tendencies to underestimate the horizontal extent of the left stimulus. However, their divergent patterns of ocular exploration and verbal responses indicate that they may have done so for different reasons. Two of the three neglect patients (C.S. and G.M.) did not show any gross asymmetries in their eye fixation patterns. The fixation pattern of the third patient (R.D.) was highly asymmetrical. Given his homonymous hemianopia, it would have been impossible for him to see any portion of the left rectangle on any simultaneous trial during the first two sessions. Yet he never complained that his task was nonsensical. Instead, on the majority of trials, he asserted with confidence that the left rectangle was the smaller (or the right the larger). Moreover, he was no more likely to make “right is smaller” judgements on trials in which the right rectangle actually was smaller than on any other type of trial. These responses suggest confabulations, with a strong bias to devalue the left side. R.D.’s behaviour suggests that apparent perceptual size underestimation can result from a high-level response bias to undervalue the left stimulus.

Patient C.S. did not differ from normal control subjects with respect to her exploratory eye movements, with the most eccentric fixations landing just short of the far end of either rectangle. However, she had a complete left homonymous hemianopia. Thus, with the exception of a few trials in which she fixated beyond the left-hand edge of the left rectangle, she would have been unable to view its full extent. Unlike patient R.D., C.S.’s “right is smaller” responses were reliably related to the stimulus dimensions. It seems plausible that her size underestimation resulted from the fact that her scanning was insufficient to ensure a full view of the left rectangle. This is consistent with the hypothesis that incomplete leftward scanning can be sufficient for size underestimation. This “oculomotor” underestimation could provide an explanation for the fact that size distortion phenomena are particularly prevalent and severe amongst neglect patients with hemianopia (Doricchi and Angelelli 1999; Ferber and Karnath 2001).

A third pattern was observed in patient G.M. Relative to control subjects, G.M.’s oculomotor exploration was biased slightly *leftwards*, possibly as a result of the scanning training that he was receiving from rehabilitation staff. Given his full visual fields, G.M. would have been able to view the entirety of all presented stimuli. His “right is smaller” responses were invariably issued on trials in which the right stimulus actually was smaller, showing that his responses were not random with respect to the stimuli presented. Nevertheless, G.M. reported that the left stimulus was smaller on 75% of trials overall. G.M.’s behaviour establishes that scanning deficiencies are not necessary for size underestimation. This third variety of size underestimation would be consistent with the hypothesis that some neglect patients perceive stimuli presented on the left side of space as compressed (e.g. Milner 1987; Bisiach et al. 1996; Milner et al. 1998). It is also consistent with recent findings of Harvey and colleagues (2003), who recorded eye movements of six patients, three of whom showed leftward size underestimation. Little relation was found between the severity of the horizontal size underestimation and asymmetry in eye movement patterns. Harvey et al. concluded that the size underestimation was not related to asymmetrical ocular scanning patterns.

In terms of our understanding of the neglect syndrome, the most important result may be that an apparent perceptual underestimation of leftward stimuli may actually reflect a high-level response bias. Indeed it could be argued that the most parsimonious explanation for the size distortion observed in all three of our patients would be a similar response bias (i.e. to choose the left stimulus as smaller when uncertain). However, previous reports show that reliable size distortion effects can be observed using a 'method of adjustment' technique (Kerkhoff 2000) or a manual size estimation technique (Pritchard et al. 1997). Neither of these findings could be explained by such a high-level response bias. Nonetheless, we would argue that the possible presence of such a high-level bias needs to be considered carefully when attempting to infer the nature of a neglect patient's perception from his or her verbal reports.

Simultaneous vs. sequential presentation

In addition to presenting pairs of rectangles simultaneously, we also presented them successively. It was expected that this external scheduling of stimulus viewing would lead to an improved symmetry of eye movements amongst neglect patients. This expectation was met in the case of R.D., the only patient to show a clear deficiency of leftward scanning in the simultaneous condition.

Despite these effects of sequential presentation on eye movements, however, we did not observe a reduction of leftward size underestimation for any patient. This contrasts with the findings of Kerkhoff (2000), who reported greatly reduced size underestimation for sequential displays. This discrepancy may be explained if, rather than considering the relative lateralization of two stimuli in egocentric (i.e. relative to the participant) co-ordinates, we focus upon their lateralization within an allocentric (i.e. relative to the environment) reference frame. We suggest that, for a patient to underestimate a leftward stimulus, they must perceive the paired stimuli to be mutually lateralized within a common environmental context.

Kerkhoff's participants were tested in dim illumination, and the stimuli were white on a black screen, the borders of which were covered by an oval black mask. During sequential presentations, the contextual cues for perceiving stimulus lateralization were sparse, thus accounting for the modest distortion effects observed. However, in Kerkhoff's simultaneous presentation condition, each stimulus would have been lateralized by the other's presence, so that strong distortion effects would be expected. In our own experiment, however, all stimuli were presented in black on a white screen in a well-lit room. Under these rich contextual cue conditions, stimuli on opposite sides of the screen would have been clearly perceived as lateralized with respect to one another, regardless of whether they were presented simultaneously or sequentially. This hypothesis also suggests a ready explanation for Karnath and Ferber's (1999) failure to observe distortion effects amongst neglect patients required to match the distances between pairs of LEDs, presented sequentially in darkness (i.e. in the absence of any environmental cues).

The effects of prism adaptation

Studies of the effects of various intervention procedures on ocular scanning have been mixed. While some reported no effect (e.g. limb activation, Brown et al. 1999), others did observe improved ocular scanning (neck muscle vibration and vestibular stimulation; Karnath et al. 1996). In the current study, two of our patients exhibited no clear scanning deficits in the baseline sessions, perhaps because our two-item matching task was too simple to expose the scanning asymmetries commonly seen in visual search tasks (e.g. Husain et al. 2001). Nonetheless, the one patient (R.D.) who did exhibit such a lack of leftward scanning during the baseline sessions, showed a dramatic improvement after the prism treatment. The fact that no change was seen in those patients who were already scanning near-symmetrically suggests that prism adaptation does not inevitably provoke changes in exploratory eye movements. Instead it may only do so where there are pre-existing deficits. Indeed, R.D.'s scanning improvement took the form of an increase in the leftward extent of fixations, without any contraction at the right-hand end of the range.

Prism adaptation had clear beneficial effects on patient R.D.'s symmetry of spatial exploration, but the strong tendency of all patients to make the first saccade rightwards during simultaneous stimulus presentation was entirely unaffected by prism adaptation. These observations suggest that the ameliorative influence of prism adaptation may lie more in facilitating voluntary spatial exploration than in altering exogenous orienting. This pattern of compensatory eye movements is reminiscent of some instances of clinically resolved neglect where an initial rightward orienting bias can nonetheless still be detected (e.g. Bartolomeo 1997; Mattingley et al. 1994; Harvey et al. 2002).

None of our patients showed a reduced size matching bias following prism adaptation. Previous studies have found an improvement from visual motion stimulation (Kerkhoff et al. 1999) but not after neck muscle vibration (Schindler et al. 2002). At face value, our data suggest that size distortions are resistant to prismatic intervention. However, this conclusion may be premature. In patients C.S. and G.M. the overall response to prism adaptation, as assessed by screening tasks, was incomplete, with improvement apparent on only one or two of the three tasks administered. Thus, these two patients provide no strong evidence for or against the idea that size matching bias is generally resistant to prism adaptation.

Patient R.D. presents a slightly clearer picture, in that the null effect of prism adaptation on his size judgements was associated with marked improvements on several neglect screening tasks, as well as on oculomotor measures. As already noted, his verbal responses were unrelated to the stimuli presented which was strongly indicative of a high-level response bias to devalue the left side regardless of sensory input. This laterally biased, but otherwise random, pattern of responses was maintained in the post-prism session. Given R.D.'s strong overall response to prism exposure (as assessed by other means), this result does suggest that his high level bias may be resistant to prism adaptation. It may be that prism adaptation has its principal benefits in tasks where some element of exploratory scanning is critical, whether externally (as in cancellation tasks: Rossetti et al. 1998) or internally (as in tests of visual imagery: Rode et al. 1998, 2001). A high-level response bias that is independent of stimulus exploration may be unaffected.

Acknowledgements This research was supported by grants from the Leverhulme Trust and the Wellcome Trust. We thank Jackie McPherson, Robin Edwards and David van Vliet for their assistance in computer programming.

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