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Ocular search during line bisection
The effects of hemi-neglect and hemianopia

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Summary
We examined ocular fixations during line bisection in five patients with left hemianopia, two patients with right hemianopia, nine patients with left hemi-neglect and nine normal control subjects. Compared with measures in control subjects, the median fixation, and left- and right-most fixations were shifted contralaterally in patients with hemianopia alone and ipsilaterally in patients with hemi-neglect. The fixation with the longest duration and the bisection point were also shifted contralaterally with hemianopia and ipsilaterally with hemi-neglect. However, the number of fixations and the spatial range spanned by fixations did not differ between the groups, showing that ocular exploration was not truncated in any group. Only some patients showed a previously reported directional search bias. Overall, there was no directional bias in saccadic number or amplitude. The distribution of fixations was most dense at the centre of the line in normal subjects, while hemianopic patients fixated most frequently at the ends of lines in their contralateral (blind) hemispace and at a central locus that was biased slightly contralaterally, as was their bisection judgement. This contralateral bias may reflect either an adaptive contralateral attentional gradient or a non-veridical spatial representation within the remaining normal hemifield. Hemi-neglect patients had a broad distribution of fixation peaks in the ipsilateral hemispace. Of two hemi-neglect patients with many fixations, one clustered fixations at a position right of centre, as if a normal fixation pattern was shifted rightward, while the other had two fixation peaks: one to the far right and the other near the centre of the line, reminiscent of the dual peaks of activity seen in some recent hemi-neglect models. These data reveal a heterogeneity in the routes by which right-biased judgements of spatial centre are reached by hemi-neglect patients.

Keywords: hemi-neglect; eye movements; line bisection; attention; hemianopia

Abbreviation: ANOVA = analysis of variance

Introduction
Hemi-neglect is a condition in which patients with cerebral lesions ignore or fail to explore all, or part, of the space contralateral to the side of their lesion. It is more frequent and severe after lesions of the right hemisphere (Albert, 1973; Chain *et al.*, 1979; Weintraub and Mesulam, 1987). While it is classically described with parietal lesions (Brain, 1941), it can occur with damage elsewhere, including the frontal lobe (Heilman and Valenstein, 1972; Damasio *et al.*, 1980; Liu *et al.*, 1992; Maeshima *et al.*, 1994), thalamus (Watson and Heilman, 1979; Watson *et al.*, 1981) and basal ganglia (Hier *et al.*, 1977; Damasio *et al.*, 1980). Hemi-neglect arises not from defects in early visual processing (Riddoch and Humphreys, 1987), but from impaired attentional processes. However, the nature of this disturbance continues to be debated (Bisiach and Vallar, 1988; Rizzolatti and Gallese, 1988). Heilman and Valenstein (1979) postulated an arousal defect they called 'hemispatial hypokinesia', with reduced actions in the neglected hemispace (Rizzolatti and Gallese, 1988). In 'directional hypokinesia', contralaterally directed movements are impaired regardless of the hemispace where the movements are occurring (Heilman *et al.*, 1985). Kinsbourne (1987) also proposed a directional bias of attentional vectors, in which neglect arises through imbalance in reciprocally inhibiting brainstem control processes of lateral orientation. Weintraub and Mesulam (1990) proposed a failure of 'selective' attention, mediated by a supramodal network of cortical and subcortical regions, independent of sensory or motor circuits. Besides attentional explanations,

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there are hypotheses of disordered internal representations of space (Bisiach and Berti, 1987) which draw support from demonstrations of neglect for visual imagery.

While these theories are not necessarily mutually exclusive, they do lead to different predictions about the behaviour of hemi-neglect patients. In particular, they vary in the predicted distribution of attention within the supposedly intact ipsilateral hemispace. In hemispatial hypokinesia (Heilman and Valenstein, 1979) attention and exploration within the ipsilateral hemispace should be normal. With Weintraub and Mesulam's (1989) model of right hemispheric dominance in selective attentional circuits, space is bilaterally represented in the right hemisphere, but only unilaterally in the left; this predicts some inattention to stimuli in the right hemispace in patients with left hemi-neglect, but with a sharp demarcation in performance at the midline (Bisiach and Vallar, 1988). Theories of biased attentional vectors also predict some inattention in the ipsilateral hemispace, but the distribution of attention should be a smooth left-to-right gradient peaking on the right, without a sharp border at the midline (Bisiach and Vallar, 1988).

Scanning eye movements are one means of exploring attentional distribution. Abnormalities in ocular search probably do not cause hemi-neglect but reflect underlying defects in orienting and attention (Riddoch and Humphreys, 1987). While there is debate over the relationship between attention and eye movements (Posner, 1980; Remington, 1980; Shepherd *et al.*, 1986), evidence indicates that a shift in attention to the region of the saccadic goal is needed to execute a voluntary saccade (Hoffman and Subramanian, 1995; Kowler *et al.*, 1995). On the other hand, attention can be shifted in space without a saccade (Posner, 1980), though there is growing evidence that attention both modifies and evokes activity in ocular motor structures like the superior colliculus (Kustov and Robinson, 1996). Nevertheless, while 'covert' orienting of attention may occur in the absence of a saccade, the distribution of saccades and eye fixations during scanning can serve as a marker of the spatial pattern of 'overt' attention (Umiltà, 1988). While previous eye-movement studies in neglect have documented the expected decrease in eye fixations in, or towards, left hemispace (Chédru *et al.*, 1973; Girotti *et al.*, 1983; Johnston and Diller, 1986; Ishiai *et al.*, 1987; Butter *et al.*, 1988; Rizzo and Hurtig, 1992; Karnath, 1994), only a few have made some analysis of the distribution of fixations within the explored range (Chain *et al.*, 1979; Ishiai *et al.*, 1989, 1992; Hornak, 1992; Karnath and Fetter, 1995).

We recently examined the ocular fixation patterns of patients as they searched an array of letters for one particular letter (Behrmann *et al.*, 1997). The distribution of fixations in any visual task is the result of a number of interacting factors. Eye movements tend to be made to prominent or 'salient' visual features. Salience is determined both by the physical properties of the stimulus, such as contrast, colour, motion and form, and by the instructional set of the subject (in the experimental context, the task they have been asked to perform). The scanning of salient features interacts further with any internal attentional biases of the subject, which are held to be minimal in normal individuals, but significant in patients with hemi-neglect. Our letter array generated a flat distribution of fixations in normal subjects (Behrmann *et al.*, 1997), suggesting that this visual stimulus/task combination had an even distribution of salience across horizontal space. In contrast, left hemi-neglect was associated with a gradient of fixations across the spatial extent of the letter array. Given an even distribution of salience in the stimulus/task, this indicated an internal attentional bias manifesting as a left-to-right gradient, consistent with neglect theories of biased attentional vectors (Kinsbourne, 1987; Bisiach and Vallar, 1988).

How would such patients perform other visual stimuli/tasks, particularly those that do not have an even distribution of salient elements? Line bisection is one such task: though the physical characteristics (luminance and contrast) of the line stimulus are evenly distributed across space, the instruction to bisect generates fixation patterns that are heavily concentrated around the centre of the line in normal subjects (Ishiai *et al.*, 1987, 1989), indicating greater salience of the mid-region of the line. Our study of ocular search with a letter array also included a line-bisection task with simultaneous recording of eye-movements. In this paper we report the analysis of that line-bisection component. We also studied the behaviour of patients with hemianopia but without neglect. Besides offering insights into the strategic adaptation of ocular search to visual loss, the hemianopic patient is an important control in hemi-neglect studies, since many patients with hemi-neglect have coexistent visual field defects from damaged optic radiations or striate cortex (Chain *et al.*, 1979; Schenkenberg *et al.*, 1980; Girotti *et al.*, 1983).

Methods

Subjects

All subjects gave informed consent, and eye-movement recording protocols were approved by the ethics committee of The Toronto Hospital. All subjects had an acuity of ⩾20/40 in both eyes with correction, and those with glaucoma, retinopathy or cataracts were excluded. All patients had homonymous visual field defects in their contralateral hemifields. These defects were assessed by confrontation and with automated perimetry (Humphrey 30–2 program). The lesions of patients were documented with either CT or MRI, and transferred onto templates from the Talairach–Tournoux atlas (Behrmann *et al.*, 1997). Most patients had cerebral infarctions, some had tumours or resections for tumours (Table 1).

Neglect was diagnosed with a standardized bedside battery of examinations (Black *et al.*, 1990), including drawing and copying tasks, a line cancellation task modified from Albert (1973), a shape cancellation task (Weintraub and Mesulam, 1987) and line-bisection tasks. Each task was scored, and

Table 1 *Patient characteristics*

Subject	Sex	Age (years)	Education (years)	Neglect score (%)	Duration (months)	Spared regions in visual hemifield	Lesion site
Right hemianopia							
DMM	F	48	?	0	8	None	Occipital-temporal
PAC	F	40	16	0	18	None	Occipital-temporal
Left hemianopia							
DL	M	66	13	2	0.25	None	Parietal, temporal, basal ganglia
PW	M	66	18	1	8	Temporal crescent	Occipital
SS	F	28	13	0	3	Inferior paracentral	Occipital
WH	M	55	10	0	17	None	Optic tract, occipital-temporal
WG	M	32	?	0	90	None	Optic tract
Left hemi-neglect							
AG	M	63	?	85	0.50	None	Parietal, basal ganglia
DD	F	61	13	75	23	None	Occipital, thalamus
ET	F	67	14	78	12	Central hemimacula	Frontal, temporal, parietal, basal ganglia
FR	M	78	12	70	10	None	Frontal, parietal, occipital
JR	F	73	11	37	9	partial upper quadrant	Frontal, parietal temporal, occipital, thalamus
HL	F	76	15	16	8	None	Parietal, temporal, basal ganglia
CP	M	57	?	100	0.25	Central hemimacula	Parietal, thalamus
AR	M	62	11	16	3	None	Occipital-temporal
JI	M	74	17	94	12	Central hemimacula	Frontal, temporal

the scores were added to give a total score out of 100; scores greater than six indicated the presence of left hemi-neglect, with higher scores denoting greater severity.

Nine normal subjects served as controls (mean age $\pm$ SD = 59.2 $\pm$ 3.4 years). Among the 16 patients tested, nine had left hemi-neglect from right hemispheric lesions (Table 1). Their mean age was 67.9 $\pm$ 7.6 years). These hemi-neglect patients all had some left homonymous visual field defects also. As additional control subjects, we also tested five patients with left homonymous hemianopia from right-sided lesions of either the occipital lobe or the optic tract (mean age 49.0 $\pm$ 18.8 years). We also tested two patients with right homonymous hemianopia from left-sided lesions (mean age 44.0 $\pm$ 5.7 years). In addition to their right hemianopia, these last two patients also had pure alexia, but this would not affect a non-lexical task like line bisection. The mean ages of these groups were significantly different from each other [$F(3,21) = 5.82$, $P < 0.025$); t tests showed that this was due to the neglect group being older than the two small hemianopic groups.

Apparatus

Subjects sat in a chair with their heads against a headrest. The room was dimly illuminated. With both eyes open, they viewed a tangent screen 1.14 m away from their corneal surface. We used a magnetic search coil technique to record eye movements, using 6-foot field coils (CNC Engineering, Seattle, Wash., USA) and a scleral contact lens worn in the right eye of all subjects. Horizontal and vertical eye positions were sampled at 200 samples per second, displayed on a rectilinear inkjet polygraph (Elema-Schönander, Stockholm, Sweden); the digitized data were stored for later analysis on a PDP 11/73 computer.

Ocular recording procedure

The system was calibrated initially by asking the subjects to follow a red back-projected laser target which moved between the centre of the screen and 20° right and left. These right and left movements were compared with each other; if there was a difference from some small inhomogeneity of the magnetic field, the right-side calibration was used and a multiplicative correction factor was calculated for left-sided data. Next, subjects looked at the four corners of the visual display boards on the tangent screen, each corner having 22.5° horizontal eccentricity and 18° vertical eccentricity. This was repeated three times to establish the eye position signals marking the display perimeter, and to verify that subjects had no limitation of ocular motility in the range spanned by the displays. The line-bisection task was only one of a number of displays presented during this session (see Behrmann *et al.*, 1997). We obtained further calibration checks before and after each display, by asking the subjects to fixate the red laser target at the centre of the screen. This ensured that the ‘zero-point’ calibration had not drifted horizontally or vertically during testing. The values of these immediate pre- and post-task zero calibration checks were averaged and subtracted from the data values obtained for the viewing of that display. These extensive calibration procedures were required to confirm the accuracy of our data concerning the position of gaze in space.

After calibration, the subjects’ view was occluded while a display was positioned. Two different horizontal line-bisection displays were used. The first (long) line subtended 45° horizontally (i.e. the whole width of the display board); the second (short) line subtended 34°. Each were black lines of 1° width on a white background, lying along the horizontal meridian (vertical position of 0°). Both were centred at the middle of the screen and, therefore, also with respect to the

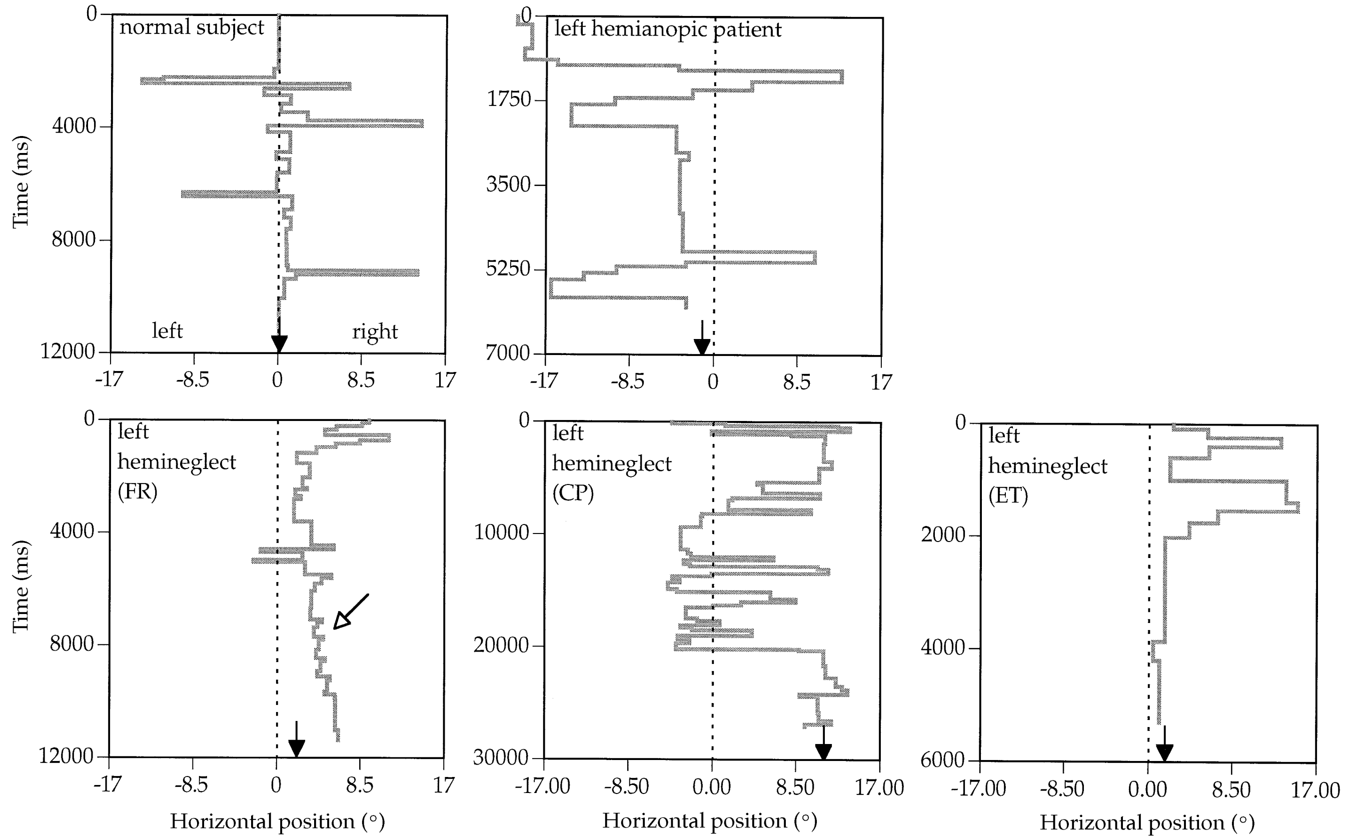

Fig. 1 Ocular search traces. Graphs were reconstructed from data on horizontal eye position and fixation duration during bisection of the short line (34° length). Horizontal eye position is plotted against time. Right = right hemispace, the dotted line represents the centre of the line, and the horizontal extent of the graph shows the length of the line. Scanning starts at time zero (top). Results are shown for a normal subject, one with left hemianopia without neglect and three hemi-neglect patients, including one (ET) that shows the directional search bias described by Ishiai *et al.* (1989). Black arrows mark the bisection point. The clear arrow indicates a segment of search by FR that displays a directional saccadic bias, with gradual drift of the search rightwards.

midline of subject, although subjects were not aware of this before viewing. The order of line presentation was random, as was the appearance of the line in the sequence of visual displays. Subjects were instructed to examine the entire line and then to use a pointer held in their right hand to touch the centre of the line. The occlusion was then removed and the subjects' eye movements recorded from this point until the moment the pointer touched the display board. The position of the pointer was noted as the 'point of bisection'.

Data analysis: summary variables

Scanning data consists of a series of small saccades separated by periods of no eye movement, which are the fixation intervals (Fig. 1). From the vertical eye position trace, it was determined which fixations lay along the plane of the viewed line, i.e. when when scanning of the line began and ended. The horizontal position and the duration of each eye fixation was determined.

For each subject, we characterized scanning with a number of 'summary variables'. For each line and each subject we recorded the total number of fixations, the median fixation, the right-most fixation, the left-most fixation, the range of fixation (the distance between the right-most and left-most fixations) and the midpoint of the range of fixation. We felt that, statistically, this array of variables would characterize scanning better than a simple mean. In addition, we noted the fixation with the longest duration, since this might indicate a locus attracting greater attention.

Two additional 'directional' summary variables were also examined. First, we attempted to replicate the finding of Ishiai *et al.* (1989) that patients with left hemi-neglect fixated at a single point in the right hemifield and restrict their search to points left of this. Using the fixation with the longest duration, we constructed an index of the time and area of search to the left and right of this fixation point, using their method (Ishiai *et al.*, 1989). Secondly, we examined the saccades made to fixation points. The distribution of fixations alone does not reveal whether there is a greater tendency to move left or right. However, the saccades made to these fixation points do contain that information. Therefore we determined the number and amplitude of rightward versus leftward saccades.

For each of the four patient groups (normal, left hemi-neglect, right hemianopia and left hemianopia) we obtained group means and standard deviations of these summary

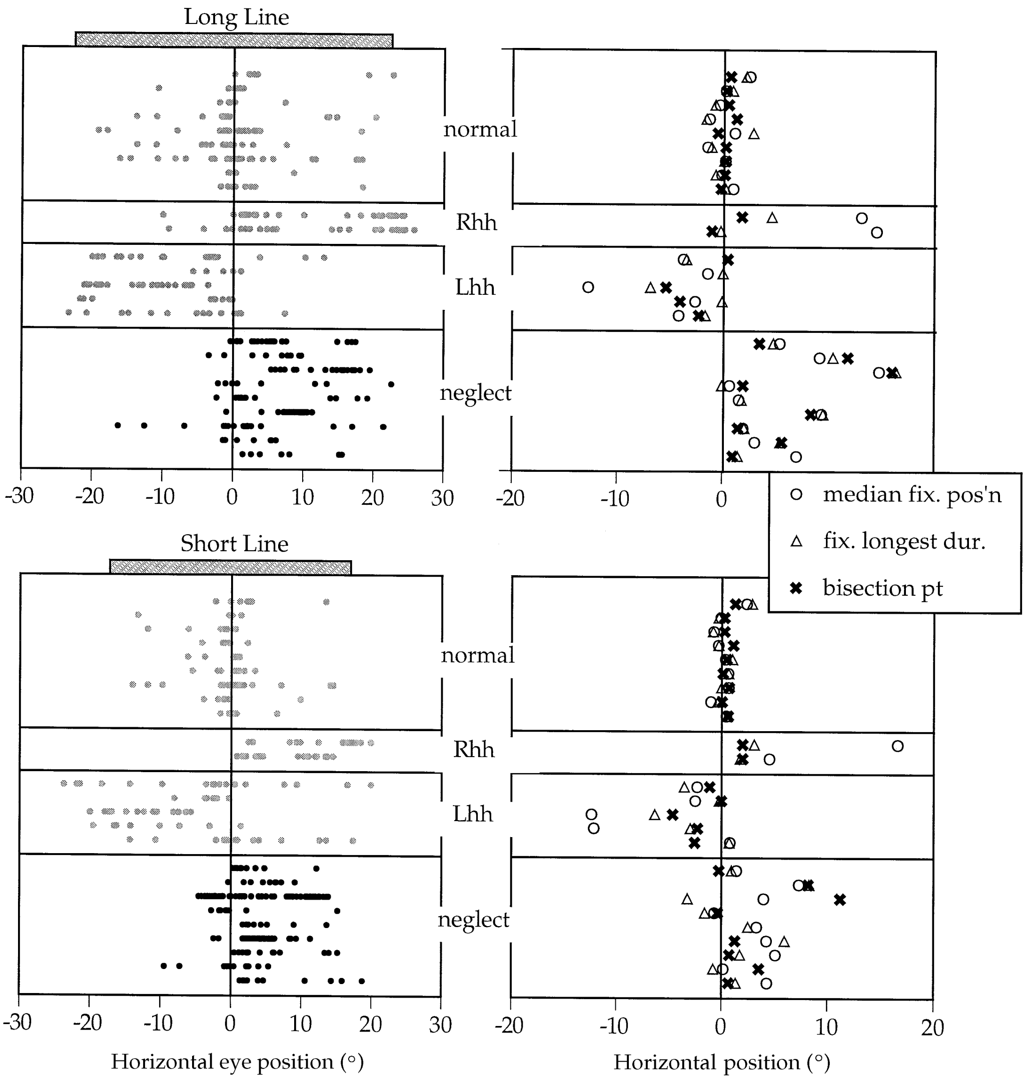

Fig. 2 Data by individual. The distribution of horizontal fixation positions are shown on the left, with each line representing an individual subject within a group, in the reverse descending order as in Table 1. Groups are separated by horizontal black lines, and are identified in the centre of the figure (Rhh = right hemianopia; Lhh = left hemianopia). Negative values indicate left of centre positions, and positive values right of centre. Top panels are for the long line, and bottom panels are for the short line, both represented in length by grey bars. The median fixation, the fixation with longest duration and the point of bisection are shown on the right, again for each individual.

variables, as well as for the point of bisection (data are missing for one hemi-neglect patient and for one line of a left hemianopic patient). We performed analysis of variance (ANOVA) with repeated measures on all summary variables, with line type (short versus long) as the repeated variable and patient group as the independent variable. We were also interested in whether any of the summary indices of ocular search correlated with the degree of hemi-neglect in the group of neglect patients. For these nine individuals we performed Spearman rank correlations upon each summary variable, first against the total score from their neglect battery testing, and secondly against their point of bisection, which we consider a 'within-examination' indicator of their neglect. We used a rank correlation method because there are no data concerning the quantitative scaling of our neglect scores.

Data analysis: fixation indices

Besides these summary variables, we were also interested in the detailed distribution of fixations during scanning. This might reveal fixation clusters indicating locations of greater salience. An index of 'overt attention' should account for both the frequency and the duration of fixations within a region. To do this we first sorted fixations by horizontal position. We then devised a moving window, spanning seven fixations, dividing the average duration of the seven by the average horizontal distance between them, and assigned this value to the middle fixation of the seven. This gives a 'fixation index' (in milliseconds per degree) indicating the time spent in the vicinity of that point.

We first performed a group analysis of fine ocular search structure, by including the fixation points of all subjects in a given group, in the process of sorting by horizontal position, and then calculated the fixation index from this group data. Next we noted that two neglect patients (CP and FR) had made a large number of fixations, sufficient to construct fixation indices for them as individuals. We performed a separate fixation analysis on these two subjects. In order to compare these two individuals' results with a recent neglect model (Anderson, 1996), we arbitrarily scaled their indices with a square-root transformation, and normalized them so that the maximum value was one.

We used Anderson's (1996) 'salience' equations to model the fixation indices of CP and FR, relating y (the salience or, in our case, fixation index) to x (the horizontal position). Because the model uses arbitrary units of spatial scaling, we first normalized each line's length to similar arbitrary units from 0 (left edge) to 1000 (right edge), with centre at 500. Essentially, $y = \mathrm{SF}/[1 + (x - \mathrm{M})^2/\mathrm{SD}^2]$, with constants M (the horizontal position of the peak value), SD (the width of the function) and SF (a scaling constant relating the height of one peak to the other when there are two peaks). Two such functions are linearly combined to model a distribution with two peaks, whereas one suffices for a distribution with one peak. We fitted our curves and derived constants with a non-linear sum-of-squares technique.

Results

Examples of reconstructed traces from the ocular search patterns in time are shown in Fig. 1, for a normal control subject, a patient with left hemianopia but no neglect and three patients (FR, CP and ET) with left hemianopia and left hemi-neglect. Individual data are shown in Fig. 2.

Summary variables (Table 2)

The four summary variables concerning scanning position in space (median fixation position, right-most fixation, left-most fixation and the midpoint of the range of fixation; see Fig. 3) all showed significant effects of group and gave very similar results. Compared with normal control subjects, patients with hemi-neglect scanned more to the right. In contrast, patients with left hemianopia but no hemi-neglect scanned more to the left than either normal subjects or hemi-neglect patients. Similarly, the two patients with right hemianopia scanned more into their contralateral blind hemispace.

The two other positional indices of attention (the fixation with longest duration and the point of bisection) also showed significant effects of group, which followed the pattern for the previous positional variables. Interestingly, hemianopic patients tended to produce small bisection errors contralaterally, contrary to the larger ipsilateral errors of patients with hemi-neglect.

On the other hand, there was no significant effect of patient group or line type on the number of fixations made, and the size of the fixation range did not differ between the groups. Thus the amount and distribution of 'overt attention', as indexed by ocular fixations, is not constricted by hemi-neglect or hemianopia, but is shifted rightwards or leftwards by these conditions.

The length of line used had an effect upon the right-most fixation and the fixation range only. The right-most fixation was further to the left with the short line, in keeping with the reduced line length, and the fixation range was smaller with the shorter line.

Interactions between subject group and line length were found. Right-most fixation was further right with the longer line in all except left hemianopic patients. The left-most fixation was further left with the longer line except in left hemi-neglect and left hemianopic patients. This is understandable since hemianopic patients cannot know contralateral line extent without looking into this region, and hemi-neglect patients do not bother to do so. The fixation range was reduced with the shorter line in all groups, but more so in normal subjects and right hemianopic patients. Lastly, the point of bisection was most affected by line length in patients with hemi-neglect; there was less ipsilateral deviation with the shorter line.

The Spearman rank correlations for the hemi-neglect group alone showed one small significant effect in comparison with the total battery neglect score; the rank coefficient (r_s) was 0.60 for the left-most fixation with the long line ($t_s = 2.00$, $P < 0.05$). In comparisons with the point of bisection, there was one significant correlation: that with the point of longest duration in the long line test ($r_s = 0.93$, $t_s = 6.11$, $P < 0.0005$). This close relationship between bisection point and fixation of longest duration in hemi-neglect patients can also be seen in Fig. 2.

Directional measures

A replication of the analysis of Ishiai *et al.* (1989), using the position of the fixation with longest duration as the border between rightward and leftward exploration, showed a significant group effect by ANOVA with repeated measures (Table 3). However, this was due to the search patterns of the hemianopic groups; the left hemianopic patients spent 75% of their search time to the left of their longest duration fixation (index (R – L/R + L) = –0.51, where an index of 0.0 indicates equal left and right search times). The two patients with right hemianopia spent 97% of their search time to the right of this point (index = 0.95). This confirms the prior observation of increased contralateral directional indices in hemianopia (Ishiai *et al.*, 1989). In contrast, the index for normal subjects was –0.17, and for hemi-neglect patients it was 0.04. Thus, as a group, hemi-neglect patients tended to search almost symmetrically, both right and left of their longest fixation point, contrary to the prior observation of Ishiai *et al.* (1989). However, individual data showed that three patients behaved according to the observations of Ishiai *et al.* (1989) for at least one line (e.g. ET; see Fig. 1).

The examination of saccadic size and amplitude did not show any significant group effects for indices of directional

Table 2 *Summary variables*

	Normal subjects	Left hemianopia	Left hemi-neglect	Right hemianopia	ANOVA *P*-values		
					Group	Line	Interaction
Number of fixations							
Long line	12.2 ± 8.5	14.2 ± 6.8	15.6 ± 8.6	26 ± 2.8			
Short line	9.4 ± 6.8	12.2 ± 4.4	18.7 ± 17.0	18 ± 1.4			
Median fixation position							
Long line	0.2 ± 1.2	–4.9 ± 4.5	5.9 ± 4.7	13.9 ± 1.0	0.001		
Short line	0.3 ± 1.0	–5.7 ± 6.1	3.3 ± 2.5	10.6 ± 8.6			
Rightmost fixation							
Long line	13.6 ± 7.5	3.6 ± 6.6	16.2 ± 5.4	25.1 ± 1.0	0.001	0.005	0.025
Short line	5.9 ± 5.5	6.6 ± 11.4	12.9 ± 3.7	17.3 ± 3.8			
Leftmost fixation							
Long line	–8.6 ± 7.5	–18.3 ± 7.2	–1.9 ± 5.9	–9.5 ± 0.5	0.001		0.025
Short line	–6.9 ± 4.8	–17.1 ± 6.1	–1.5 ± 3.7	1.7 ± 1.1			
Fixation range							
Long line	22.3 ± 11.0	21.9 ± 10.6	18.1 ± 9.0	34.6 ± 0.5		0.01	0.025
Short line	12.8 ± 6.8	23.6 ± 14.2	14.5 ± 3.1	15.6 ± 2.7			
Midpoint of range							
Long line	2.5 ± 5.1	–7.4 ± 4.4	7.1 ± 3.4	7.8 ± 0.8	0.001		
Short line	–0.5 ± 3.9	–5.3 ± 5.7	5.7 ± 3.4	9.5 ± 2.5			
Fixation of longest duration							
Long line	0.3 ± 1.5	–2.4 ± 2.9	5.8 ± 5.4	2.2 ± 3.4	0.005		
Short line	0.3 ± 1.1	–2.5 ± 2.8	1.7 ± 3.6	2.4 ± 0.9			
Point of bisection							
Long line	0.4 ± 0.5	–2.8 ± 2.5	6.3 ± 5.5	0.4 ± 2.0	0.01		0.005
Short line	0.6 ± 0.4	–2.1 ± 1.7	3.2 ± 4.3	2 ± 0.0			

Means ± SD are given. Results for ANOVA with repeated measures are on the right are, with *P*-values for effect of subject group, line length, and interaction between the two.

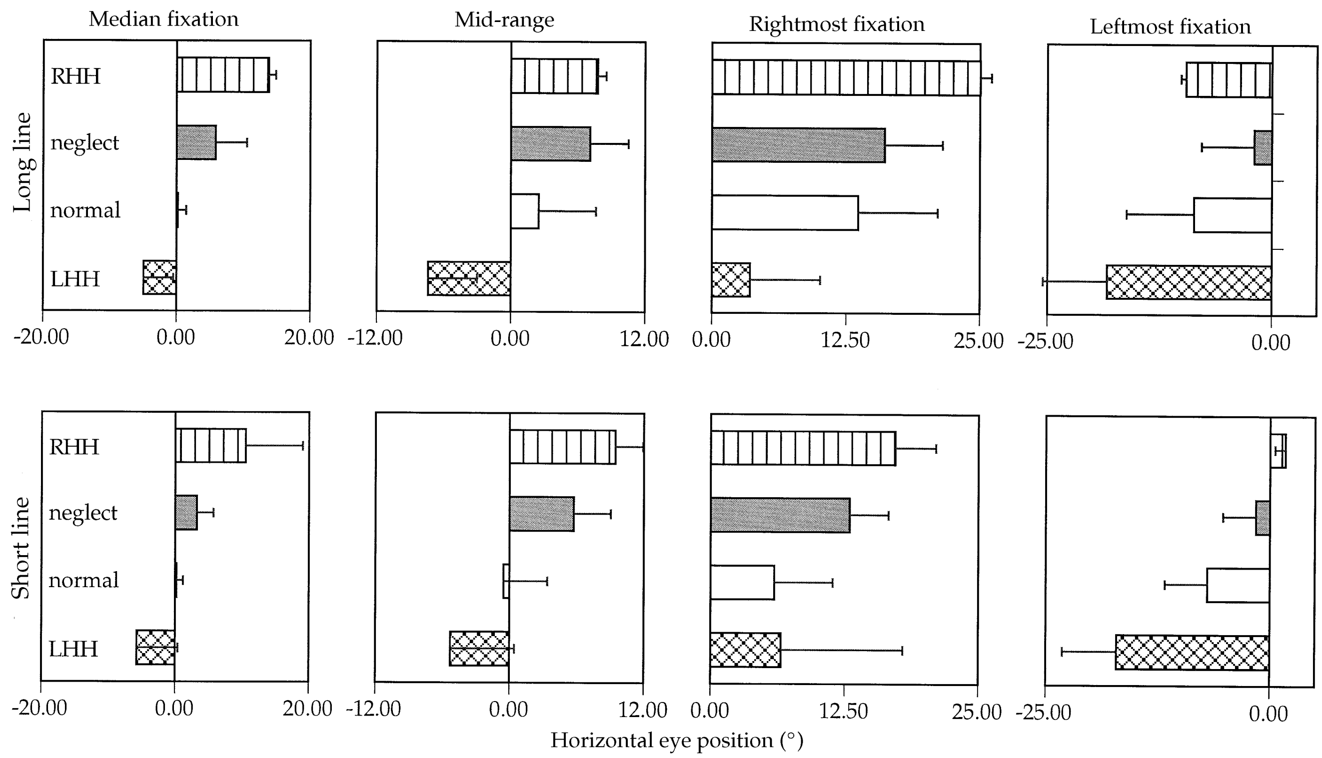

Fig. 3 Summary variables. Group means of horizontal positional are shown for the median fixation, the midpoint of the range scanned, and the right- and the left-most fixations. Error bars show the standard deviation. LHH = left hemianopic group; RHH = right hemianopic group.

Table 3 *Variables related to rightward and leftward movement*

	Normal subjects		Left hemianopia		Left hemi-neglect		Right hemianopia	
	Leftward	Rightward	Leftward	Rightward	Leftward	Rightward	Leftward	Rightward
Ishiai (1989) index								
Long line	0.08 ± 0.07	0.12 ± 0.18	0.28 ± 0.31	0.07 ± 0.07	0.05 ± 0.04	0.06 ± 0.06	0.01 ± 0.01	0.53 ± 0.05
Short line	0.06 ± 0.03	0.02 ± 0.02	0.42 ± 0.37	0.06 ± 0.06	0.09 ± 0.15	0.08 ± 0.08	0.01 ± 0.01	0.40 ± 0.19
Saccadic number								
Long line	4.8 ± 3.5	6.4 ± 5.1	6.8 ± 4.2	6.4 ± 2.6	6.6 ± 4.1	8 ± 4.8	11.5 ± 8.7	13.5 ± 3.5
Short line	4.3 ± 4.2	4.1 ± 2.8	5.8 ± 2.7	5.4 ± 1.8	8.9 ± 7.8	8.8 ± 9.9	9 ± 1.4	8 ± 0
Saccadic amplitude								
Long line	6.9 ± 3.6	6.3 ± 2.5	5.7 ± 3.1	6.9 ±2.7	4.1 ± 2.3	3.6 ± 1.3	9.5 ± 0.5	8.2 ± 1.7
Short line	3.5 ± 2.3	3.8 ± 1.7	5 ± 1.7	5.8 ± 2.9	3.3 ± 1.1	3.7 ± 1.6	4.9 ± 1.5	5.2 ± 1.1

The mean values (± SD) of the Ishiai index (see text), and number and amplitudes of rightward versus leftward saccades are shown.

symmetry (Table 3). However, there was a group effect for saccadic amplitude, with hemi-neglect patients making the smallest saccades of all groups, both rightward and leftward, for both lines. Nevertheless, visual inspection of traces showed that, in some hemi-neglect patients, there were short segments of ocular search that did suggest an ipsi-directional (rightward) saccadic bias (e.g. FR; see Fig. 1).

Fixation index (group analysis)

The vast majority of fixations in normal subjects were centred around the midpoint of the line (Fig. 2), which is reflected in the fixation index for this group (Fig. 4). In contrast, those with hemianopia had distinctively different fixation patterns, with the fixation index of right hemianopia mirroring that of left hemianopia. These groups tended to have a twin-peaked distribution. One peak was near the centre of the line but shifted by 2–4° into the hemispace ipsilateral to their hemianopia (contralateral to their lesion). The second peak coincided with the termination of the line in their blind hemifield. Thus, these patients concentrate fixations at the end of the line which they cannot see with their peripheral vision, and at a central location which is also skewed into their blind hemifield.

The hemi-neglect group performed differently from both normal subjects and those with hemianopia. They had a multi-peaked distribution, mostly within ipsilateral hemispace. Unlike hemianopic patients, they lacked a peripheral fixation peak at line end.

Fixation index (individual analysis)

The broad multi-peaked fixation index of the hemi-neglect group may result from heterogeneity of neglect, both in type and severity. However, two hemi-neglect patients made sufficient fixations to allow a fixation index to be constructed from their individual data. Patient CP was a 57-year-old man who had had a right hemispheric stroke 1 week before testing. He also had an old right occipital stroke causing left hemianopia, and an old left peri-occipital stroke. The new lesions coincided with the onset of left hemi-neglect and were in the right parietal region and the right posterior thalamus and internal capsule (Fig. 5). Patient FR was a 78-year-old man whose right hemispheric stroke had occurred 2 years previously. His stroke affected two cortical regions, one in the frontoparietal junction, the other in occipitoparietal cortex (Fig. 5). Both these patients had left homonymous hemianopia, left hemiparesis and severe neglect.

The fixation index was plotted against horizontal fixation position (Fig. 6). Patients CP and FR differed markedly in their spatial allocation of fixations; FR had a single peak to right of midposition, whereas the fixation index for CP had two peaks, one towards the right end of the line and another near the middle. With the long line, this second peak was right of the middle, but with the short line, it was actually in left hemispace.

The fixation indices of CP and FR were modelled with Anderson's (1996) functions (Fig. 6). For FR, a single function fits the data well. For CP, the summation of two such functions is required to account for the twin peaks; his data is the first direct demonstration of dual fixation peaks during overt attention. The derived constants are given in Table 4, together with the values used in Anderson's model (Fig. 7).

Discussion

With a variety of indices of the spatial position of ocular search, we found that the scanning of left hemi-neglect patients is shifted ipsilaterally (rightward), whereas that of patients with either right or left hemianopia without neglect is shifted contralateral to their lesion. These indices include right-most, left-most, median and midrange fixations, as well as the fixation of longest duration. However, the number of fixations and the relative size of space scanned are similar in both hemianopia and hemi-neglect, showing that neither condition results in reduced search or a constriction of scanned space.

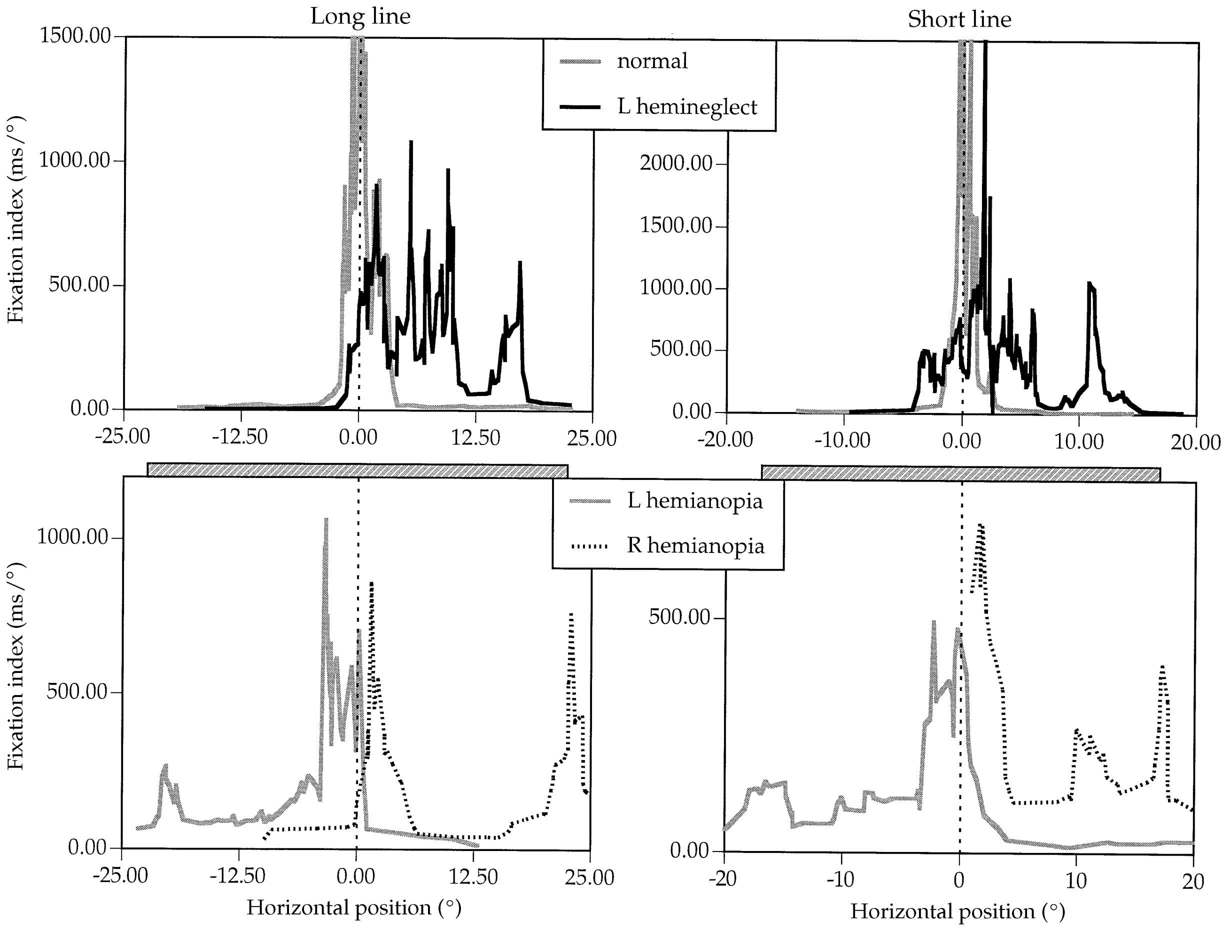

Fig. 4 Group fixation indices. The indices (ms per degree) of the four groups are plotted against horizontal position. The large central peak of normal data is truncated. The horizontal hatched bars show the position and lengths of the long and short lines.

On average, there was no directional saccadic bias, though hemi-neglect patients did tend to make smaller saccades, and some patients had short segments of search with saccadic bias. Similarly, although a few patients showed the directional search bias described by Ishiai *et al.* (1989), this was not a general feature of the group. However, we did find that, for the long line at least, the point of bisection correlated with the fixation of longest duration.

Analysis of the fine structure of ocular search showed that normal subjects mainly scanned the centre of the line symmetrically, and they seldom looked towards the ends of lines (Ishiai *et al.*, 1987, 1989). Hemianopic patients had twin peaks of fixation: one at the line end in their contralateral blind hemispace (Ishiai *et al.*, 1989) and one near the centre of the line, which was slightly contralaterally biased. Hemi-neglect patients displayed a broader distribution of fixations in ipsilateral hemispace. Study of two such patients with many fixations revealed markedly different patterns of ocular search, with one (FR) showing a single right-shifted peak of fixation activity, and another (CP) showing twin peaks of activity, one near the centre of the line and one in peripheral right hemispace.

Scanning in hemianopia

Although it can be difficult to disentangle hemianopia from hemi-neglect (Meienberg *et al.*, 1986; Walker *et al.*, 1991), patients with hemi-neglect often have coexistent hemianopia (Chain *et al.*, 1979; Schenkenberg *et al.*, 1980; Girotti *et al.*, 1983). Therefore their behaviour must be compared with that not only of normal subjects but also of patients with hemianopia alone.

With simple saccadic targets in the blind hemifield, hemianopic patients make a ‘staircase’ series of small searching saccades which diminish with predictability (Meienberg *et al.*, 1981; Girotti *et al.*, 1983; Rizzo and Hurtig, 1992). With more complex displays, some studies show little effect of hemianopia on scanning; using complex drawings, Rizzo and Hurtig (1992) found symmetric hemispatial distributions of fixations, and Chédru *et al.* (1973) found that visual field defects had no effect on hemispace exploration time. On the other hand, a contralateral bias can be shown in other tasks. We previously found that hemianopic patients showed a spatial gradient of fixations biased towards contralateral hemispace, which was essentially the mirror image of the effect seen in hemi-neglect patients (Behrmann

Fig. 5 Right hemispheric lesions of FR and CP, on the bottom and top, respectively. Template drawings are shown of axial sections, anterior = top. CP's lesions involve the parietal lobe, posterior thalamus and posterior internal capsule; there is also an older peri-striate lesion (arrow) as well as a similar old lesion of occipital cortex in the left hemisphere. FR's lesions affect the temporoparieto-occipital region and the frontoparietal region.

et al., 1997). With line bisection, hemianopic patients concentrated fixations in the periphery of their hemianopic field (Ishiai *et al.*, 1987), often scanning to the edges of lines (Ishiai *et al.*, 1989). With respect to their bisection point, hemianopic patients searched more in contralateral hemispace (Ishiai *et al.*, 1989). In the present study we have observed both of those aspects of line-bisection behaviour.

Fixational search patterns represent an interaction between internal attentional biases and salient display elements, which are determined by the physical properties of the stimulus and the instructional set of the subject. Our prior study used a display that generated a flat distribution of fixations in normal subjects, suggesting an even distribution of salience across the letter array. Hemianopic search patterns with this letter array had a gradient of fixations peaking contralaterally (Behrmann *et al.*, 1997), indicating a contralateral attentional bias, probably arising as a strategic adaptation to hemianopia in patients aware of visual loss. On the other hand, the ocular search of normal subjects in line bisection (Ishiai *et al.*, 1987) suggests a salience distribution heavily weighted to the centre of the line. In the hemianopic bisection search we see the interaction of this centrally weighted salience with an adaptive attentional gradient. Thus, twin fixation peaks emerge, one near the centre of the line and a smaller peak at the contralateral end of the line, a point with understandably greater significance to hemianopic patients.

We found also that the central peak of fixation activity was shifted contralaterally in hemianopia; furthermore, hemianopic bisection points were also contralaterally shifted. Previously, Gassel and Williams (1963*b*) commented that some hemianopic patients positioned the eyes 'eccentrically towards the hemianopic side'. They also noted contralateral ocular deviation with eye closure (Gassel and Williams, 1963*a*), but this correlated with impaired ipsi-directional pursuit and optokinetic nystagmus. A small contralateral bias has been noted in other samples of hemianopic patients (Liepmann and Kalmus, 1900; Barton and Black, 1998). The origin of the contralateral bisection and fixation bias in hemianopia is not clear, but it may be a consequence of the adaptive attentional gradient just described. Alternatively,

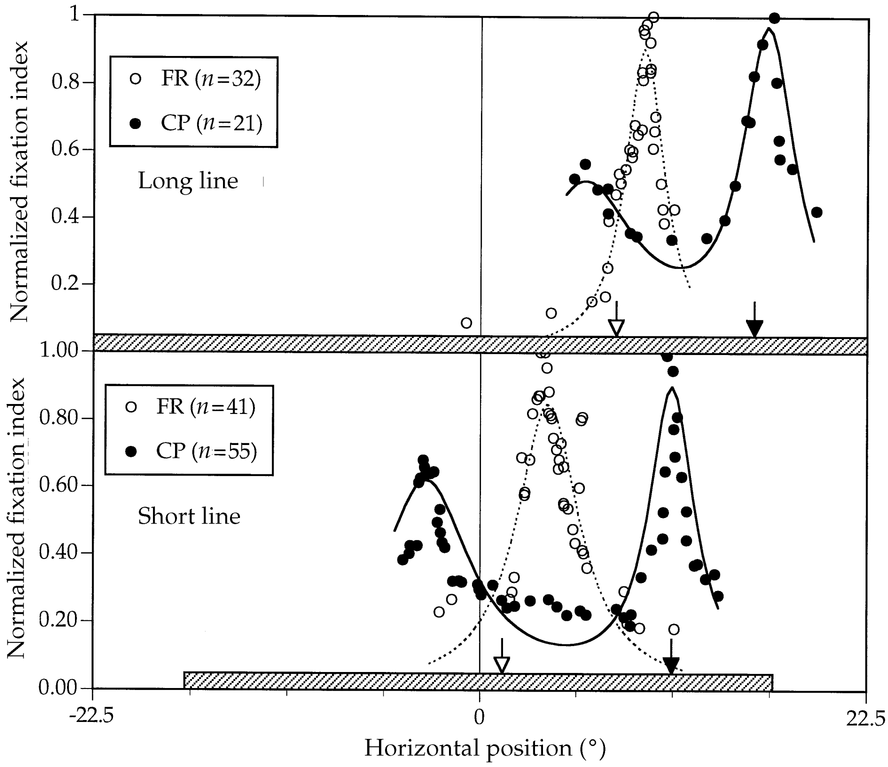

Fig. 6 Fixation indices of FR and CP. Top panel shows the indices with the long line, and the bottom panel those with the short line; 'n' is the number of fixations each patient made per task. Curves are the modelled salience functions using Anderson's (1996) equations, $y = \mathrm{SF}/[1 + (x - \mathrm{M})^2/\mathrm{SD}^2]$ (see text). A combination of two functions describes the twin-peaked data of CP (solid curve), whereas one function describes the data of FR (dotted curve). Grey bars indicate the horizontal extent of the long and short lines. White arrows show the bisection judgements made by FR, and the black arrows those of CP.

since hemianopic patients can only view the entire line when it is placed in one hemifield, this bias may indicate that spatial representation within one hemifield is non-veridical and weighted in favour of the central field. More study is required to determine the origin of contralateral hemianopic bias. In any case, this contralateral bias in hemianopia makes the ipsilateral deviation in hemi-neglect patients, many of whom have coexistent hemianopia, all the more deviant.

Scanning in hemi-neglect

Standard saccadic tests have shown that hemi-neglect patients frequently fail to make saccades to left-sided targets, even with predictable targets (Girotti *et al.*, 1983; Butter *et al.*, 1988; Rizzo and Hurtig, 1992). This may reflect failure of sensory attention, motor intention or both (Butter *et al.*, 1988). More complex scanning studies document decreased left hemispatial search. With letter or symbol arrays, left hemispatial exploration time is decreased in severe hemi-neglect (Chédru *et al.*, 1973), and it correlates inversely with neglect severity (Johnston and Diller, 1986). We reported decreased left hemispatial scanning of a letter array with a fixation gradient across space, indicating a pathological ipsilateral attentional gradient, quite different from the adaptive contralateral attentional gradient in hemianopia (Behrmann *et al.*, 1997). Decreased left hemispatial scanning occurs with displays of line drawings and photographs (Chain *et al.*, 1979; Rizzo and Hurtig, 1992; Karnath, 1994) or even during searches for a non-existent target in the dark (Hornak, 1992; Karnath and Fetter, 1995).

Ocular search during line bisection has been studied by Ishiai *et al.* (1987, 1989, 1992). Their bin analysis suggested that hemi-neglect patients made equal numbers of fixations in both hemispaces (Ishiai *et al.*, 1987). In contrast, we found asymmetrical search patterns. All our measures of scanning position in space were displaced rightward in a remarkably consistent pattern. The large bin sizes used by Ishiai *et al.* (1987) may have obscured this rightward shift. Later, Ishiai *et al.* (1989) reported that hemi-neglect patients fixated on a right-sided position and only searched ipsilateral to this point. Though they failed to search left of this position and therefore had not seen more of the line's leftward extent because of hemianopia, they bisected not at the midposition of the line segment seen but at their left-most fixation, suggesting a 'line completion' effect (Ishiai *et al.*, 1989, 1992). We saw this only occasionally (ET), and our overall group results did not conform to this pattern. In some cases (e.g. CP) there was evidence of a leftward search which did not influence

Table 4 *Constants in the salience function equations*

	Long line	Short line	Anderson (1996)
Subject CP			
Left peak			
Scaling factor (SF)	1	1	1
Width (SD)	45	45	100
Peak position (M)	865	825	750
Right peak			
Scaling factor (SF)	0.53	0.70	1
Width (SD)	95	95	75
Peak position (M)	630	410	480
Subject FR			
Single peak			
Width (SD)	30	65	
Peak position (M)	710	615	

The constants SF, SD and M were used in the equations relating y (salience) to x (horizontal position) in Figs 2 and 3: $y = \mathrm{SF}/[1 + (x - \mathrm{M})^2/\mathrm{SD}^2]$. CP's data and Anderson's model are fitted by the sum of two such functions, one for a left peak (right hemisphere's contribution in the model) and one for a right peak (left hemisphere's contribution). The arbitrary units for horizontal position place the centre, aligned with the centre of the object viewed, at 500 (object-referenced). A key difference is that Anderson places 0 (left end) and 1000 (right end) at the limits of space (spatial scaling), whereas CP's and FR's constants are derived with 0 and 1000 at the limits of each object (object scaling). With object scaling, the position (M) of CP's left peak is similar for the short and long lines.

the bisection decision (Ishiai *et al.*, 1996). Rather, CP's bisection was made as if the leftward components of search had not occurred at all.

There are few data on directional eye-movement effects in hemi-neglect. The rapid eye movements of sleep show more rightward than leftward movements with hemi-neglect (Doricchi *et al.*, 1993). However, similar but less pronounced ipsi-directional (rightward) biases were also seen in patients with hemianopia alone. In our study we cannot confirm a similar tendency in either saccadic amplitude or number for the hemi-neglect group. However, inspection of traces does show segments when a directional drift in ocular search appears. Therefore, it is premature to conclude that a directional imbalance to saccades does not exist at all, although its contribution to the overall ipsilateral skewing of hemi-neglect search seems to be minor.

The group fixation indices were not as clear-cut for hemi-neglect as for hemianopia. In general, there was a broad multi-peaked distribution of fixation activity skewed towards ipsilateral (right) hemispace. This broadness probably stems, at least partly, from heterogeneity in neglect severity. Additional heterogeneity in the qualitative nature of search is revealed by the fixation indices of patients CP and FR, which differed from each other even though both made right-biased judgements of the centre of the line. Since their idiosyncratic search patterns were replicated with a second line, it is likely that these reflect something of the altered distribution of attention in each.

For FR, the fixation index suggests a shift of attentional reference coordinates into the right hemispace, as if a large portion of left hemispace is omitted from representation and fixations cluster around the new centre of the remaining representation. Similar 'frame-shifts' have been found in hemi-neglect eye movements in the dark (Karnath and Fetter, 1995). Frame-shifts can be predicted from several older theories of neglect (Heilman and Valenstein, 1979; Heilman *et al.*, 1985; Weintraub and Mesulam, 1987). CP's twin peaks are more problematic for such theories, but may conform to a recently described 'salience function' (Anderson, 1996). This function postulates two peaks of activity, one from each hemisphere, and it was developed to explain why neglect patients paradoxically bias bisections of short lines leftward (Marshall and Halligan, 1990) and why, when they are shown a point that is the centre of an imaginary line and they are asked to mark the ends of that line, they place the left end more peripheral than the right end (Bisiach *et al.*, 1996).

When comparing Anderson's (1996) model and CP's data, differences in scaling factors and curve widths may reflect variations in neglect severity, and curve widths can also be altered by scaling transformations; hence, these are trivial differences. However, differences in peak positions suggest that the model requires modifications. First, the position of CP's right peak (representing the left hemisphere's salience function) is skewed further rightward than that in the model. Secondly, Anderson's model centred the salience function over the object of interest but scaled it according to space, not object size (in order to explain paradoxical leftward bisection of short lines in hemi-neglect). However, CP's right-most peaks (and FR's single peak) occur in different spatial positions in the short- and long-line trials, and appear more proportional to line length (Table 4). This suggests that, for large lines at least, object size influences the spatial scaling of salience. Thirdly, the variability in the position of CP's left peak is difficult to explain by either spatial or object-scaling alone; its most constant relation is its distance in degrees from the right peak. This may represent confounding issues such as interactions between separate space- and object-scales, or even different influences upon scaling for the different peaks.

Thus, while Anderson's model provides a possible explanation of the dual peaks in CP's search, it cannot explain his data entirely without including modifications to account for possible interactions between spatial scales and relative object-based scales. It is also noteworthy that the second peak does not appear to influence CP's bisection judgement, whereas such hypothesized influence provided the impetus for the creation of the salience model, to explain the bisection findings of Bisiach *et al.* (1996) and Marshall and Halligan (1990). Lastly, we note that the salience theory could also explain the emergence of a single-peak distribution, like FR's, if the salience peak of the right hemisphere was entirely eradicated. However, the values from Anderson's model and the data of CP suggest that, in that circumstance, the remaining salience peak should be displaced much further

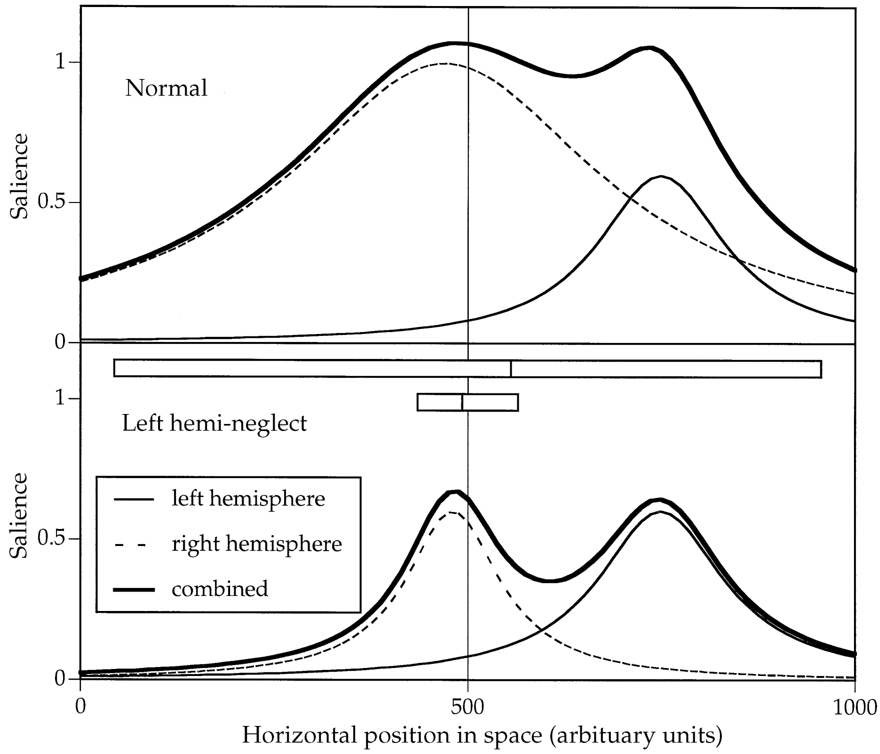

Fig. 7 Model of salience function (Anderson, 1996). Salience is the degree to which a spatial position attracts attention. There are separate salience functions for the right and left hemispheres. It is hypothesized that, normally, the right hemispheric salience function is centred just left of centre (position = ±500 arbitrary units of horizontal space), and is broader and greater than that of the left hemisphere, which is skewed to the right (top panel). The overall salience function for the subject is the sum of these two curves (combined). In left hemi-neglect (bottom panel), the right hemispheric salience function is reduced and narrowed, with emergence of twin peaks of salience activity in the combined function. Note the similarity of the neglect combined function here to CP's performance, especially with the short line (Fig. 6).

rightwards than that obtained with FR's data. The variation in FR's peak with line length also indicates the presence of some object-scaling effects. Thus important modifications to the salience theory are required if it is also to explain FR's data.

Of course, CP's data does not prove the salience model or exclude other potential explanations of his unusual ocular search pattern. For example, 'lesions' in a computational network model of perception and attention called MORSEL can simulate many features of hemi-neglect (Mozer *et al*, 1997). Inspection of their data (their fig. 10) shows that twin spatial peaks of activity are indeed present early on, when <30 iterations have occurred in the model, but they have gone by the time 50 iterations have been completed. It may be that iterations in this model correspond to some degree with duration of search in a human subject. If so, studies of the temporal evolution of search patterns may provide more data to distinguish between the salience model and MORSEL: twin peaks are prominent early but disappear later with MORSEL, whereas no such temporal variation is predicted by the salience model in its current form.

Why do CP and FR differ in their ocular search patterns? One possibility is anatomical differences. FR's lesions affect frontoparietal and occipitoparietal cortex, whereas CP's lesions affect not only parietal cortex but the thalamus: hence the differences may reflect variations in the representation of spatial attention between regional components of an attentional network (Mesulam, 1981). Differences in lesion duration are another possibility. Perhaps the twin-peaked salience function characterizes spatial distortions in attention near the time of onset, as in CP, but long-term adaptation within the attentional network is paralleled by evolution into a single right-shifted peak of attention, as in FR. Clearly, more study is required to address these issues.

Prior evidence for heterogeneity of hemi-neglect syndromes is based on double dissociations between different measures of neglect, such as ocular versus manual search (Bisiach *et al.*, 1995), line cancellation versus line bisection (Binder *et al.*, 1992), or sensory versus motor aspects (Butter *et al.*, 1988; Liu *et al.*, 1992). Our data suggest a further heterogeneity, in that right-biased decisions in the same task can be reached by very different ocular search patterns, some representing a directional search bias with a line-completion effect (Ishiai *et al.*, 1989), some representing a frame-shift of search (as with FR) and others showing twin peaks of fixation distribution (as with CP). Study of the process by which hemi-neglect patients arrive at their perceptual bias will yield further insights into the different pathophysiologies of this syndrome and, possibly, their anatomical correlates.

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