1997

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PII: S0028-3932(97)00058-4

Neuropsychologia, Vol. 35, No. 11, pp. 1445–1458, 1997

Printed in Great Britain
0028-3932/97 $17.00+0.00

Impaired visual search in patients with unilateral neglect: an oculographic analysis

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(*Received* 11 *December* 1996; *accepted* 21 *April* 1997)

Abstract—The attentional deficit underlying hemispatial neglect was examined through a detailed analysis of the eye movement performance of a group of neglect patients. Relative to normal subjects and to patients with hemianopia without neglect, patients with left neglect make fewer fixations and have shorter inspection time on the contralesional left side. They also start their search to the right of the midline and make significantly more fixations and longer fixations on the ipsilesional right side. A positive linear relationship between horizontal location and frequency of fixations was noted for the neglect group as a whole, as well as for most of the individual patients. These findings strongly endorse the view that the attentional deficit in neglect follows a left–right gradient. The peak of the maximum fixations, however, is not on the extreme right, as might be predicted by a strict gradient account, and is more consistent with recent views that the midsagittal plane of the viewer is redirected rightwards. These findings provide a detailed analysis of the eye movement patterns in neglect patients and demonstrate the robustness of oculographic analysis for examining their altered spatial representation. © 1997 Elsevier Science Ltd

Key Words: unilateral neglect; eye movements; attention; spatial attention.

Introduction

Patients suffering from hemispatial neglect, usually acquired following a right parietal lesion, typically fail to report or respond to information on the contralesional, left side of space [5, 21, 52]. An outstanding question is: what mechanism gives rise to this disturbance in visuospatial behavior? One generally accepted view is that these patients fail to distribute visuospatial attention volitionally to the side opposite the lesion and, subsequently, the representation of this contralateral information is impoverished [4]. When explicitly directed to information on the left side, however, the patients can represent and process the information presented in that region [58], further confirming the view that the patients suffer from an attentional rather than a primary sensory deficit.

Notwithstanding the general agreement that the deficit is one of visuospatial attention, there is less agreement concerning the exact nature of the distribution of attention in these patients. Kinsbourne [40–42] proposed as the basis of the deficit an imbalance in lateral orienting tendencies with excessive orienting towards the ipsilesional side. Following a right-sided lesion, for example, the leftward directed attentional vector is inactivated, with the result that the rightward vector is now unopposed. The powerful rightward vector mediated by the left hemisphere biases orientation to the ipsilesional right side. This orientational bias gives rise to a gradient of attention with a gradual decrement in processing across the visual space. Importantly, on this account, the probability of detecting a target is incrementally increased as the target is shifted towards the ipsilesional side, but the relative imbalance between two separate points on the left–right dimension is preserved irrespective of the absolute location of these points.

This gradient view contrasts with the view of a step function as suggested by Heilman *et al.* [23–26]. According to their account, each hemisphere is responsible for the orienting responses to the opposite half of space, with head and body axes determining the midline between right and left sides. Following a right-sided lesion then, one would expect to see a decrement in processing information on the contralesional left side. In contrast, pro-

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cessing would be normal on the ipsilesional right side, and there would be a marked discontinuity across the midline.

There have been two lines of work with neglect patients that have investigated these alternative accounts and both have favored Kinsbourne's view. In a series of reaction time studies, Làdavas *et al.* [46–48], for example, showed that neglect patients detected the target more poorly in the relative left than right of six horizontally arrayed boxes, even for those boxes just in the right hemispace. Interestingly, the patients detected targets in the right-most targets significantly faster than did the normal control subjects (also see [14]), suggesting that, in addition to the failure to process contralateral items with a gradual left–right fall-off, patients also show hyperattention or a stronger bias to allocate attention to the most ipsilesional items [13, 40, 46].

The second line of work involves eye movement studies which have recorded the number of fixations patients make while searching for a stimulus. These latter studies operate on the logic that because eye movement behavior parallels that of the underlying spatial attention [20, 27, 33, 44, 65, 66] (but see [43] for a somewhat different view), studying the distribution of eye movements will reveal whether the attentional deficit is best characterized by a gradient or step function. A number of eye movement studies have already characterized the abnormal pattern in patients with neglect and have shown that these patients make fewer ipsilesional than contralesional saccades, are slower to initiate leftward saccades, make multiple small saccades to locate the contralateral target, have prolonged search times for ipsilesional targets and adopt a rightward (rather than leftward) position for starting their visual exploration [8, 15, 19, 30–32, 62]. This abnormal pattern not only manifests in visual search [8], but is also seen in tracking single and double targets [20], in scene and face viewing [39, 59] and in text reading [38, 50].

Although these studies have carried out oculographic analyses of the eye movements of neglect patients, they have not specifically addressed the question of how attention is distributed. Recently, there have been a few studies which have been designed specifically to examine this issue and have plotted the patients' fixations as a function of horizontal location. In these studies, neglect patients (and their matched control subjects) explored space in complete darkness in the absence of a visual stimulus. This method was chosen specifically so that no data-driven information could influence the patients' spontaneous ocular behavior. Hornak [28] had five neglect patients search in a dark room and then plotted the proportion of fixations that fell into 5° sectors covering an area of $\pm 35°$. Karnath *et al.* [37, 38] adopted a similar design but had their subjects seated in a bulb-shaped cabin and plotted eye movements in 5° sectors over $\pm 50°$.

The findings of these studies are remarkably consistent in that ocular exploration was confined almost entirely to the right side of the midsagittal plane and, moreover, the patients explored more on the right side than did the control subjects. Both of these studies provide strong support for Kinsbourne's view in that the mean percentage of fixations fell off gradually from right to left. Although these findings are strongly suggestive of a gradient, precise details are not available. For example, in both these papers, the exact slope of this gradient function is not computed and, in addition, the data are plotted at a fairly macroscopic scale (in 5° sectors). What also remains unclear from these studies is whether the particular pattern is limited to a situation in which subjects search in the dark or whether a similar pattern is seen in a more natural free-vision situation when a display is presented to the subject in full view. The goal of the current paper is to examine in fine detail the distribution of eye movements across space when subjects are required to conduct a systematic search of a relatively complex visual scene. In addition to plotting the distribution, we also examine a host of other spatial and temporal parameters to better characterize the nature of the attentional distribution in a relatively large group of neglect patients.

Subjects performed a letter detection task, searching for a target 'A' amongst a random array of letters (see Fig. 1). Unknown to the subjects, the letters were arranged so that an even number of As occurred in each of four predefined vertical bands. This type of task is standardly used for the assessment of neglect and is considered to be sensitive even to mild neglect deficits [53]. In addition to the neglect group, we included two control groups, one consisting of age- and education-matched subjects with no history of neurological disease, and the other consisting of brain-damaged patients with visual field defects but with no evidence of hemispatial neglect. The initial dependent measures included the overall number and duration of fixations calculated across the entire search space. We then conducted more specific analyses by examining percentage and duration of fixations as a function of horizontal left–right extent (first measured in quadrants and then in more fine-grained 2° sectors). According to the orientational bias model of attention [40–42], eye movements should differ between the three

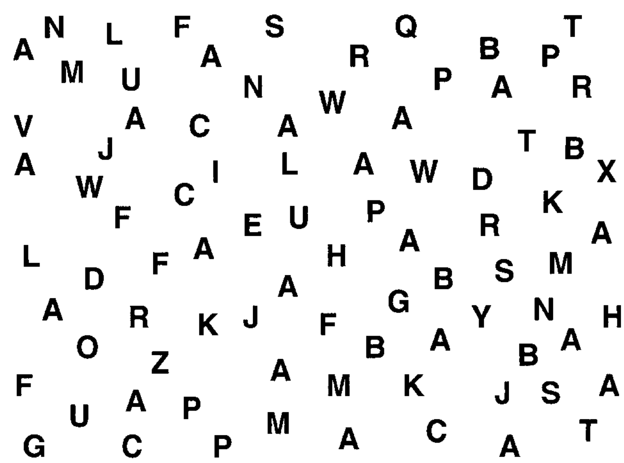

Fig. 1. Display for the visual search experiment.

groups as a function of horizontal target location, with the neglect patients showing a decreasing number of fixations from right to left. Moreover, if the bias to the ipsilesional right is strong in the patients, then one might also see more fixations (and longer duration) on the right than is even the case for the normal subjects. Additional analyses demonstrating that this gradient is specific to the right–left extent (and does not apply in the vertical dimension) and data assessing other aspects of the search performance (e.g., location of initial starting fixation) are also described.

Methods

Subjects

All subjects consented to participate.

(1) The *Neglect* group was composed of nine right-handed, English-speaking patients (four men, five women) with left hemineglect, as diagnosed by a series of bedside tests and a CT-documented unilateral cerebral lesion, as well as an MRI scan (where available). Subjects were at least 3 months post-stroke at testing and were medically stable. The mean age of these subjects was 64 (S.D. 5.6) years and the mean education level was 11.7 (S.D. 4.1) years. All had a visual field defect to some degree as measured using Humphrey automated threshold perimetry (30-2 program). In all cases visual acuity was at least 20/40 with correction.

Neglect was diagnosed on the basis of a standardized battery of examinations which included drawing and copying tasks, a line cancellation task (modified from [1]), a shape cancellation task and a line bisection task. A score was assigned for each test reflecting the degree of neglect, relative to the performance of a group of age-matched normal control subjects [6, 7]. The cumulative maximum neglect score based on these four tests was 100, with a score of 6 or greater being classified as neglect, and higher scores denoting increased severity: scores of over 75 indicate severe neglect, scores below 30 indicate mild neglect and those in between indicate moderate neglect. Demographic details, lesion site and volume, visual field defects and neglect scores for the nine neglect patients are shown in Table 1 and templates depicting their cerebral lesions are illustrated in Fig. 2.

(2) The *Hemianopic* group consisted of one female subject and three males. The mean age of the group was 53.8 (S.D. 17.9) years. None of these subjects had cataracts, retinopathy or glaucoma and all had visual field defects (Humphrey automated threshold perimetry 30-2 program). The subjects were medically stable and showed no evidence of neglect on the screening tests described above. The patients DL and PW missed two and one items on the figure cancellation test, respectively, giving them a score of 2 and 1 each. These scores are well within the normal range of performance. Templates depicting the cerebral lesion for these four hemianopic patients are shown in Fig. 3, and the demographic and data from the neglect testing are shown in Table 2.

(3) A *Control* group of subjects with no history of neurological disease was made up of nine subjects (four male, five female) drawn from the elderly subject pool at the Rotman Research Institute of Baycrest Centre, Toronto. All subjects were right handed and English speaking. No subject scored more than the cut-off of 6 points on the neglect tests. The mean age of these subjects was 59.2 (S.D. 3.4) years, not significantly different from that of the neglect patients [$F(1,17)=0.02$, $P>0.5$]. Their mean years of education was 13.1 (S.D. 2.9), also not different from the neglect patients.

Apparatus

Subjects were seated in a chair in a dimly illuminated room with the head supported in an occipital rest. Eye position and movement were measured using the magnetic search coil technique with 6-foot field coils (CNC Engineering, Seattle, WA, U.S.A.). System bandwidth was 0–400 Hz. Subjects wore a scleral contact annulus in one eye while they viewed the target display. The system had a resolution, after analog to digital conversion, of about 1 min. At the beginning of the session, the coil was placed in the right eye following a drop of topical anesthetic and it remained in place for about 30 min. A screen on which the stimuli were presented was located 1.14 m from the subject and viewing was binocular.

The signal from the eye tracker was sampled every 5 msec (i.e. 200 samples per second) by computer. The analytic program

Table 1. Demographic, lesion and neglect details for the nine target patients

Patient	Sex	Age	Years of education	Neg. score	Time test.*	Perimetry†	OR/OT‡	Lesion§	Volume
1. AG	M	63	?	85	23	Hemi, Msplit		BG	56.1
2. AR	M	62	11	16	3	Hemi, Msplit	OR	O	46.6
3. DD	F	61	13	13	24	Hemi, Msplit	OR	O	85.2
4. ET	F	67	14	78	9	Hemi, Mspare	OT	F, P, T, BG, Th, IC	129.4
5. HL	F	76	15	16	10	Hemi, Msplit		P, T, IC, BG	31.4
6. HI	M	74	17	94	23	Hemi		F, T, P	15
7. JR	F	73	11	37	4	Lower quad, Msplit	OR, OT	F, P, T, IC, BG	61.2
8. FR	M	78	12	97	7	Hemi, Msplit	OR	T, P, O	36
9. OH	F	74	9	88	11	Hemi, Mspare	OR, OT	T, O, BG, Th, IC	39.6

*Time of testing onset in months.
†Msplit, macular split; Mspare, macular sparing; Lower quad, lower quadrantanopia; Hemi, homonymous hemianopia.
‡Involvement of: OR, optic radiation; or OT, optic tract.
§F, frontal; P, parietal; T, temporal; O, occipital; IC, internal capsule; BG, basal ganglia; Th, thalamus.

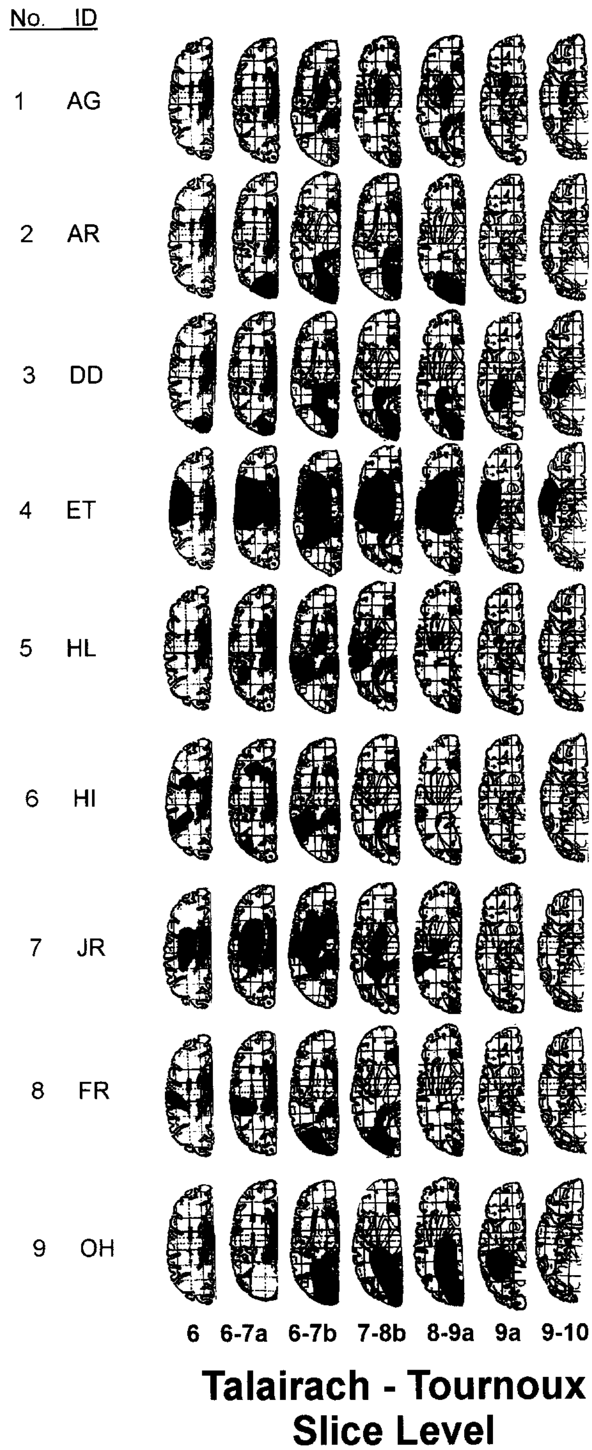

Fig. 2. Depiction of lesion sites for the neglect patients on standardized templates. Adapted with permission from [61].

identified the start and end of saccades. Fixations were defined as the interval of stable horizontal and vertical eye position between the end of one saccade and the start of the following saccade: the output of the algorithm was a series of horizontal (X) and vertical (Y) coordinates of each fixation period and its corresponding fixation duration (Z). The analog signals were digitized and stored on a hard disk off-line for later analysis, using an interactive program on a PDP 11/73 computer. Eye position was also recorded simultaneously on a rectilinear ink-jet polygraph (Elema-Schönander, Stockholm, Sweden).

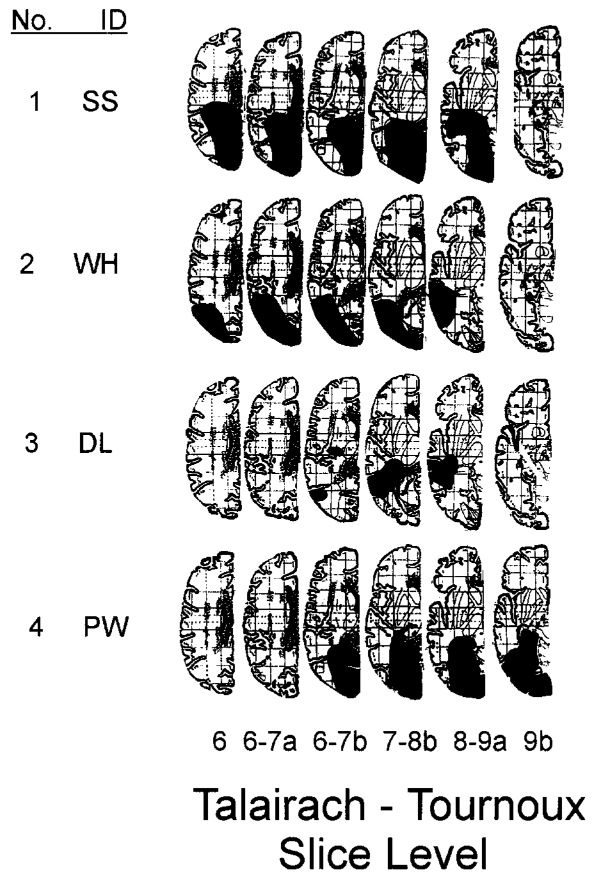

Fig. 3. Depiction of lesion sites for the hemianopic patients on standardized templates. Adapted with permission from [61].

Procedure

Calibration. Before collecting the data on the search task, the signals from the coil were calibrated by having the subject fixate spots of light located at various places on the screen. A red spot of light, subtending 1° of visual angle, was backprojected onto the center of the screen and the zero point (0,0) calibration was verified. Once this was established, the subject was instructed to look at a black dot (0.5° of visual angle) that appeared at each of the four corners of a large screen placed in front of the subjects (each corner was located at $\pm 22.5°$ horizontal and $\pm 18°$ vertical). Fixation of these five positions (zero and the corners) was repeated three times to establish the perimeter and center of the board and to check the calibration. Once the coordinates were established, the experiment was begun. The zero point calibration was repeated again after the experiment to ensure that no shifts in coordinates had taken place during the course of the experiment.

Visual search task. In this search task, letters of the alphabet appeared randomly positioned on a board (adapted from [53]; Fig. 1) subtending 45° (± 22.5°C) and 36° ($\pm 18°$) of visual angle horizontally and vertically, respectively. Recent evidence has suggested that the larger the spatial extent of the stimulus array, the more severe the neglect deficit [17]. The letters were printed in black ink in bold upper case Geneva font on a white background, and each letter subtended 1° of visual angle, well within the resolution of the eye tracker system. Subjects were instructed to search the board for all instances of the letter A, to state when the task was complete and to report the number of A letters found. There was no time limit. There were 20 instances of the letter A randomly intermixed with 64 distractor letters. Five As were positioned in each of four predetermined

Table 2. Demographic, lesion and neglect details for the four hemianopic patients

Patient	Sex	Age	Years of education	Neg. score	Time test.*	Perimetry†	OR/OT‡	Lesion§	Volume
1. SS	F	28	13	0	14	L Hemi, Msplit	OR/OT	O, T	103
2. WH	M	55	?	0	11	L Hemi, Msplit	OR	O, T, P	86.5
3. DL	M	66	13	2	13	L Hemi	OR	P, T, BG	25.8
4. PW	M	66	18	1	22	L Hemi, Msplit	OT/OT	O, Th	111.9

*Time of testing onset in months.
†Msplit, macular split; Mspare, macular sparing; Lower quad, lower quadrantanopia; Hemi, homonymous hemianopia.
‡Involvement of: OR, optic radiation; or OT, optic tract.
§P, parietal; T, temporal; O, occipital; BG, basal ganglia; Th, thalamus.

and equally spaced vertical bands. There were 24 distractor letters in the outer right and left bands, with the remaining 40 letters divided equally across the two inner bands. This layout was not known to the subjects.

Results

All the neglect subjects were able to perform the calibration procedure; occasionally, the experimenter had to instruct them verbally to look to the left, but the subjects were able to make saccades and hold fixation on the upper and lower contralesional corners of the screen. The behavioral results (the number of As reported by the subjects) are presented first, followed by detailed eye movement analysis of the three groups.

Behavioral results

On average, the control group reported a mean of 18.3 (S.D. 2.3), the hemianopic group a mean of 18 (S.D. 1.5) and the neglect group a mean of 13.6 (S.D. 1.5) instances of the letter A [$F(2,19)=15.9$, $P<0.001$]. Whereas the control and hemianopic groups did not differ from each other in their search performance [$F(1,11)=0.08$, $P>0.5$], the neglect patients differed significantly both from the normal controls [$F(1,16)=26.1$, $P<0.0001$] and from the hemianopic subjects [$F(1,11)=23.8$, $P<0.005$]. Although these data do not unambiguously reflect the left-sided neglect (as there is no way of knowing directly from the subjects' report whether the omissions were solely from the contralesional side), these findings are perfectly consistent with the fact that visual search tasks of this sort characteristically elicit omissions in patients with neglect. Also, the data from the eye movement pattern presented below strongly suggest that the omitted letters are from the contralateral side.

Analysis of horizontal eye movements

Before describing the fixation patterns for each group broken down by their distribution in the vertical and horizontal quartile bands, the total number and duration of fixations across the entire screen are presented. Figure 4 shows the mean number and mean total duration of eye fixations for the three subject groups.

Overall, the control group made significantly more fixations than the hemianopic group [$F(1,11)=5.1$, $P<0.05$], but both groups made an equivalent number of fixations to that of the neglect patients [controls vs neglect: $F(1,16)=0.6$, n.s.; hemianopic vs neglect: $F(1,11)=3.4$, n.s.]. The finding that hemianopic subjects made fewer fixations, at least in comparison with the control subjects, might be attributed to the fact that these subjects were younger than those in the other groups and that, despite their hemianopia, their speed of processing visual stimuli might accordingly have been faster. This reduction in eye movements may, however, also arise from sampling bias; there are only four hemianopic patients in the group and so this pattern may not reflect the performance of the hemianopic population at large. There were no differences in the total duration of fixations (total exploration time) between any pair of the three groups [neglect vs control: $F(1,16)=4.1$, n.s.; neglect vs hemianopic: $F(1,11)=2.8$, n.s.; control vs hemianopic: $F(1,11)=0.21$, n.s.]. These findings suggest that, for the most part, the global performance characteristics were similar for the different groups.

Because the absolute number of fixations differed across groups, the data were normalized and the analysis done on the percentage of fixations or of duration in each band, respectively (as in [28, 36, 39]). Figure 5a and b show the distribution of the percentage of fixations or durations, respectively, for the three groups as a function of left–right band.

A two-way analysis of variance with group (control, neglect, hemianopic) as a between-subjects factor and vertical band (1, 2, 3 and 4) as a within-subjects factor was conducted first on the percentage of fixations and then on the percentage of duration of those fixations. For the percentage fixations as shown in Fig. 5a, there was a significant interaction between group and band [$F(6,57)=6.4$, $P<0.0001$]. Tukey *post-hoc* tests at $P<0.05$ revealed significant differences between all three groups at the far-left band (1), no significant difference between the groups at the near-left quartile (2), and a difference between the neglect patients and the other two

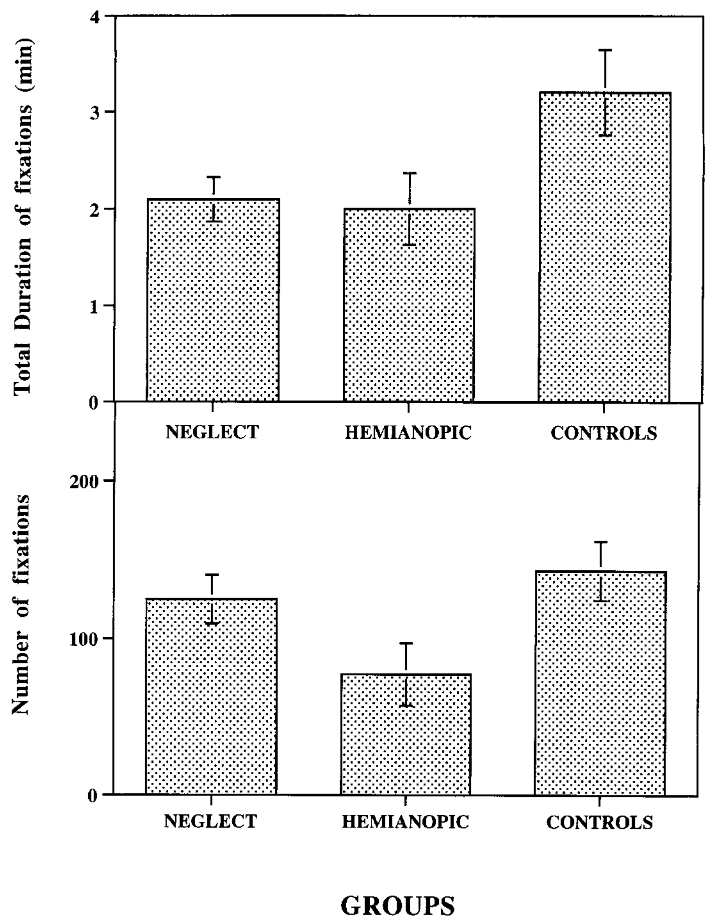

Fig. 4. Mean total number of fixations (a) and duration of fixations (b) for the control, neglect and hemianopic groups.

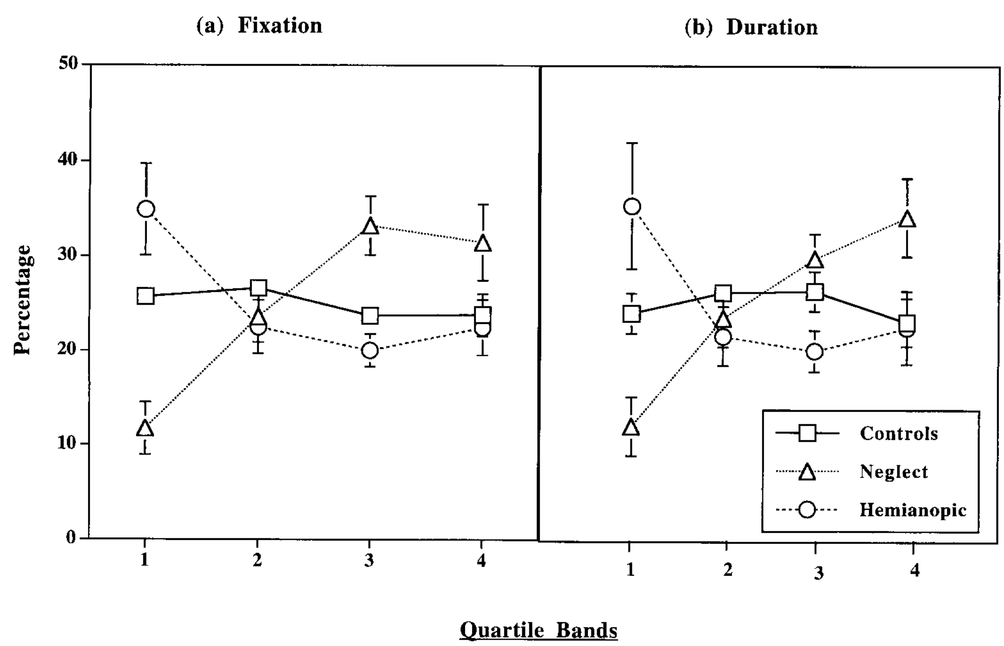

Fig. 5. Percentage of fixations (a) and duration (b) as a function of vertical band for the neglect, hemianopic and control subjects The bands referred to as far-left, near-left, near-right and far-right correspond to the numbers 1–4.

groups (which do not differ from each other) in both the near-right and far-right quartiles (3 and 4). There was also a significant main effect of group [$F(2,19)=61$, $P<0.01$]. The results of the duration analysis are identical to those of the fixation analysis, with one small difference: in the near-right band (3), all three groups differed significantly from one another but, as in the previous analysis, the neglect patients took the longest time in this band, followed by the normal control and then the hemianopic patients [$F(6,57)=4.9$, $P<0.001$].

These results reveal that, whereas normal control subjects execute approximately the same number of fixations and spend approximately the same amount of time in each of the four bands, this is not the case for the other two groups. Neglect patients make significantly fewer fixations and spend less time on the left than they do on the right of the display. Furthermore, on the right of the display (quartiles 3 and 4), they make many more fixations and these fixations are also longer in duration than is the case for the other two groups. As is evident from both panels in Fig. 5, the eye movements reflect a gradient from extreme right to extreme left for the neglect subjects. In contrast, patients who are hemianopic but do not have neglect spend considerably longer than either of the other two groups in searching for letters in the far-left band, but perform equivalently to the normal controls in the remaining bands.

A more precise quantification of the proportion of fixations as a function of horizontal position was carried out to provide a fine-grained measure of the eye movement distribution. Bands of 2° of visual angle were demarcated and the mean proportion fixations across subjects in the three groups was calculated for each band, as shown in Fig. 6. Regression analyses were performed for each of the three groups on the proportion of fixations regressed against horizontal location. There was no relationship between the horizontal position and fixation pattern for the control group [$F(1,32)=0.002$, $P>0.5$], confirming that the eye movements are distributed evenly across the visual field for the normal subjects. However, there was a significant negative linear relationship for the hemianopic group [$F(1,32)=4.7$, $P<0.05$] and a significant positive linear relationship for the neglect group [$F(1,32)=3.15$, $P=0.05$]. The negative slope for the hemianopic group confirms the increase in left-sided fixations and the compensatory saccades which sometimes extend even beyond the left end of the boundaries of the search board. Finally, for the neglect group, the slope is precipitously positive, reflecting a left–right gradient with decreasing probability of fixations towards the left of the board.

Since patients with neglect were able to move their eyes over to the left (both in the calibration procedure and in the task itself), the paucity of contralateral fixations and search time is not due to a fundamental oculomotor problem. These patients make fewer saccades into the left than into the right side of space and the left-sided fixations that they do make are rather brief. This pattern is not simply the product of a group average; rather it is seen in almost all of the individual neglect subjects. A stringent test of this is to examine the distributions for each of the neglect subjects individually. Figure 7 illustrates the distribution for each patient with fixations, depicted as circles, superimposed on the search board, which is div-

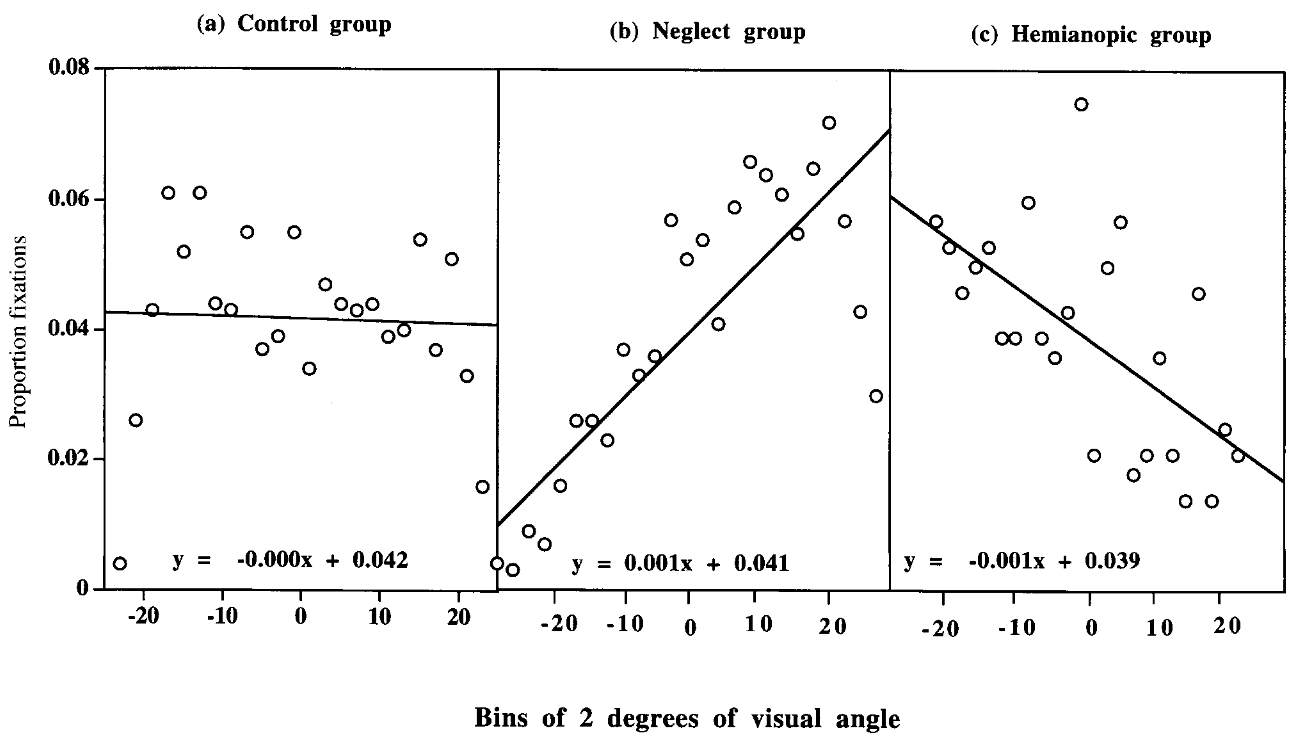

Fig. 6. Regression plots of proportion fixations against horizontal position in 2° sectors for the neglect, hemianopic and control groups.

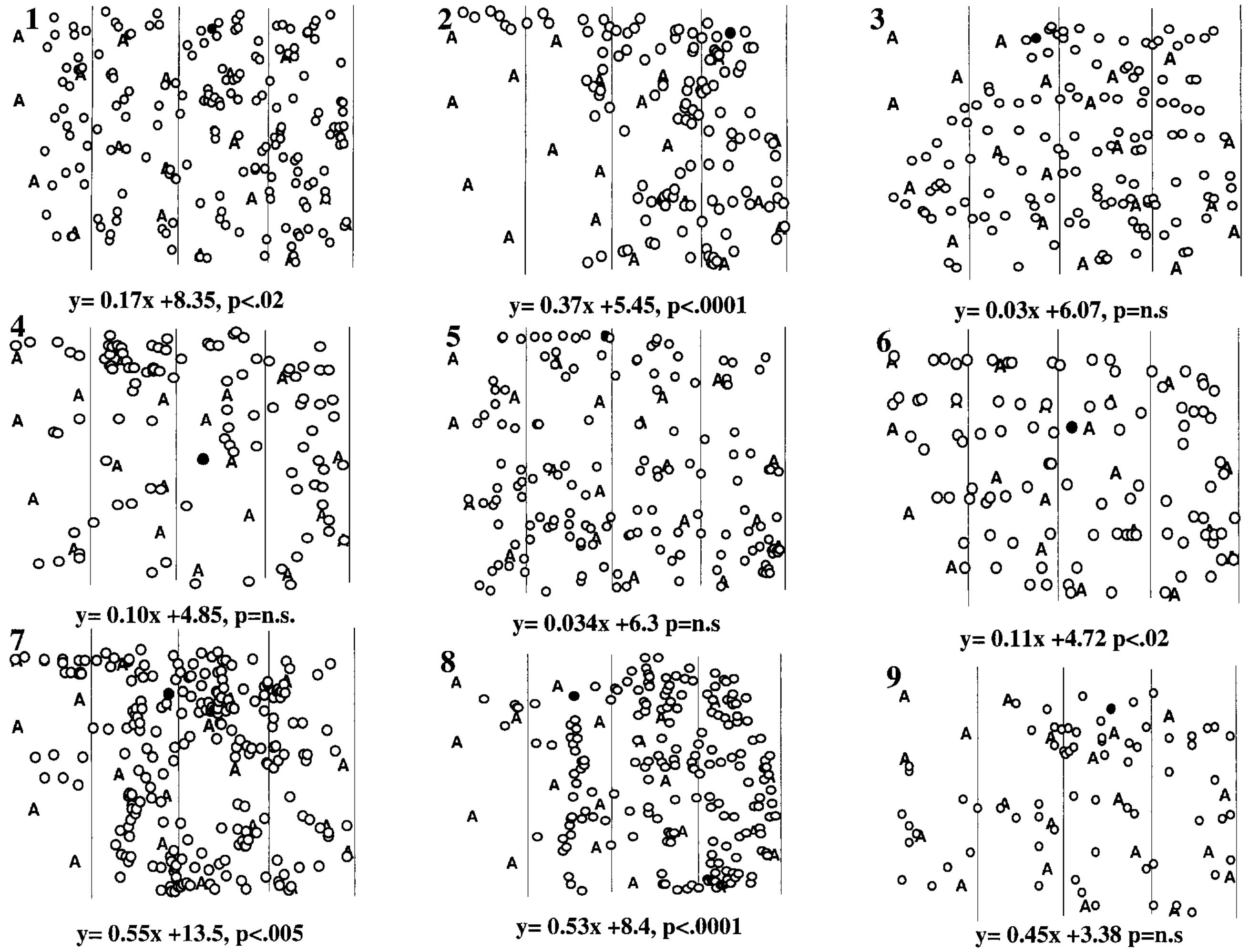

Fig. 7. Displays of fixation patterns for the nine neglect patients individually. The numbers reflect the patient numbers as shown in Table 1. The darkened circle indicates the starting fixation.

ided into the four bands. The slopes of the regression line for each subject were obtained by regressing the number of fixations per 2° band plotted against horizontal position, and the results (and significance value of the regression analysis) for each individual subject are noted below the corresponding figure. As is obvious from this figure, a reduction in the number of fixations to the left and a disproportionate increase of fixations to the right are the differentiating and hallmark patterns in neglect: the characteristic left-sided reduction and right-sided increase is seen in all to a greater or lesser degree. The regression analysis shows that horizontal position is a significant predictor of the frequency of fixations in five of the nine subjects. In two more subjects (4 and 9), there is a trend towards significance and in the remaining two subjects (3 and 5), the relationship between position and fixation frequency is weak.

The findings from the individual subjects show that the data observed in the subjects obey the gradient function, although there is some individual variability in the strength of the function. The signature pattern in these patients is a significant but gradual fall-off in the number of fixations as horizontal position moves leftwards. These results, evident even in the individual patterns of the subjects, strongly support Kinsbourne's view of neglect.

Analysis of vertical eye movements

One firm prediction of Kinsbourne's hypothesis is that the deficit in neglect patients should be restricted to the left–right dimension, whereas up–down processing should mirror that of normals. To evaluate this prediction, we compared the fixations for bands delineated in the top-down dimension. For the purpose of analysis, the visual field was divided into four rows or bands of approximately 9° each and the number and duration of fixations were calculated. It is important to note that none of the neglect subjects showed top–bottom altitudinal neglect [55, 60] as measured on vertical line bisection in the bedside screening battery.

The percentage of fixations and their relative duration in each of the four horizontally defined bands (top, above midline, below midline, bottom, corresponding to num-

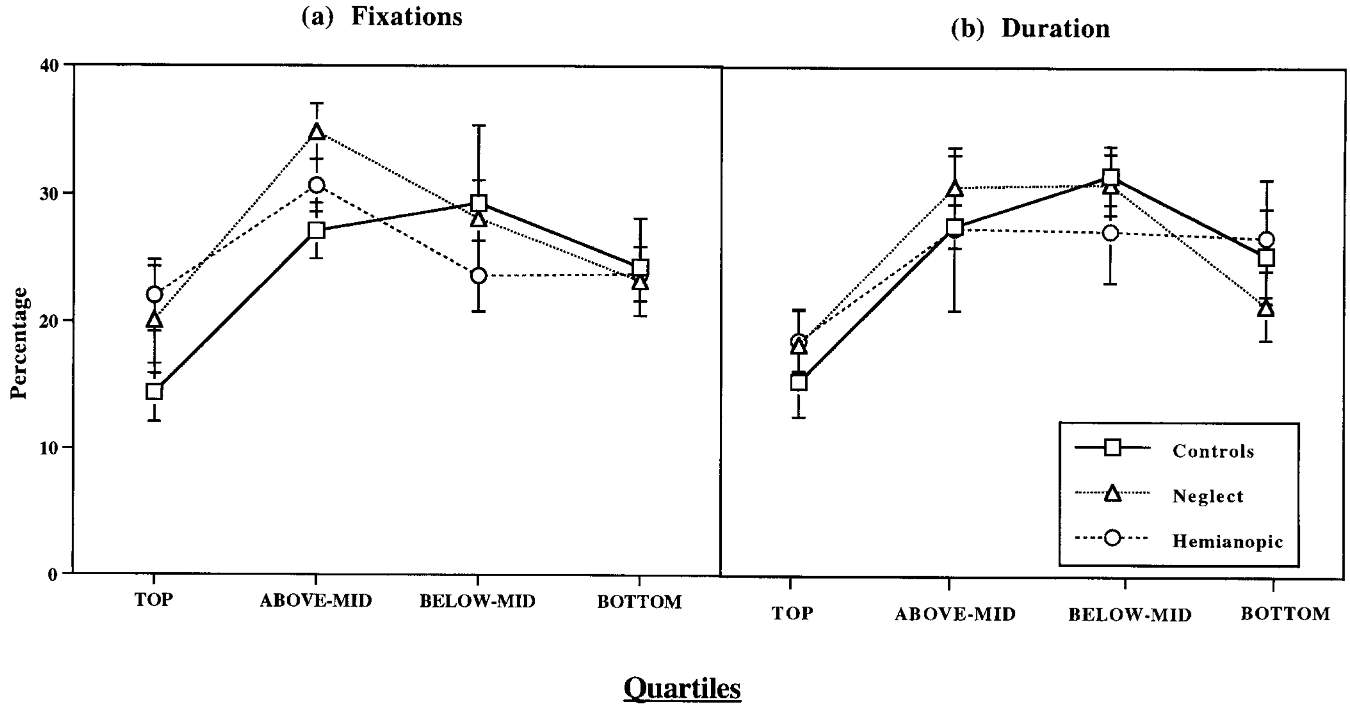

Fig. 8. Percentage of fixations (a) and duration (b) as a function of horizontal band for the control, neglect and hemianopic subjects.

bers 1–4) were measured for each subject and are shown in Fig. 8a and b, respectively. A two-way analysis of variance, with quartile (1, 2, 3 and 4) as a within-subject factor, group (control, neglect, hemianopia) as a between-subject factor and percentage of fixations as the dependent measure, showed no interaction between group and vertical band [$F(6,57)=0.51$, $P>0.5$]. Similarly, no joint effects of group and vertical band [$F(6,57)=0.95$, $P>0.1$] were seen when percentage duration per band was used as the dependent measure. Neither analysis shows a significant difference between groups [percentage fixations: $F(2,57)=1.8$, $P>0.1$; percentage duration: $F(2,57)=0.74$, $P>0.1$]. The analyses, however, showed significantly fewer and briefer fixations in the topmost band than in any other band, when collapsed across the three groups [percentage fixations: $F(3,57)=6.4$, $P<0.01$; percentage duration: $F(3,57)=6.8$, $P<0.001$].

Importantly, the results indicate that, in the vertical dimension, the pattern of eye movements does not differ between the three groups. This is in marked contrast to the finding from the horizontal analysis, which showed large discrepancies between the three groups. These findings suggest, then, that the difficulty for the neglect group is restricted to eye movements along the horizontal left–right dimension.

The results reported above are relatively straightforward and conform well with views that propose that attention is distributed along a gradient in neglect, with differing probabilities of target detection as a function of left–right position. These data also support the abnormal orientational bias to the right. In the remainder of the paper, we examine two further measures that shed light on the distribution of attention and eye movements. The first concerns the locus of the initial fixation, which is taken as an indication of the initial bias of the subject. The second analysis examines the percentage of saccades made in a rightward and leftward direction. Both these measures have previously been shown to be good measures for characterizing qualitative aspects of how attention is distributed in visual search [37, 67].

Locus of starting point

When normal subjects explore visual images, the starting point is usually influenced by the nature of the scene. For scenes containing faces or pictures, eye movements often cluster on points of salience or interest [49, 56, 59]. In contrast, on visual search tasks similar to the one adopted in this study, there is generally a slight preference for the upper left quadrant when the stimuli are scattered randomly throughout the field [8], and this bias to start on the left is even stronger when the stimuli are ordered in straight lines from left to right [34] or when subjects are reading text [39, 56]. To determine whether neglect subjects are sensitive to this constraint, we compared the starting locus of the three groups of subjects. The initial fixation for each of the neglect subjects may be seen in Fig. 7, where the darkened circle in each plot indicates the first fixation. Statistical analysis of the starting locus across the groups reveals a significant difference in the locus of the initial fixation [$F(2,19)=3.98$, $P<0.05$].

Whereas the hemianopic and normal subjects did not differ from each other and both started on the upper left quadrant, with the mean locus at $-12.1°$ and $-11.1°$, respectively [$F(1,11)=0.02$, n.s.], the neglect subjects differed significantly from both the normal [$F(1,16)=7.3$, $P<0.05$] and the hemianopic subjects [$F(1,11)=6.7$, $P<0.05$], with a mean fixation locus to the right of the midline at 2.4°. The finding that neglect patients begin their eye movements from the right of the midline is consistent with reports of other studies using different techniques and paradigms [8, 19], and reflects a strong rightward bias of attention as predicted by the gradient account.

Direction of search

The finding that neglect patients start their search to the right of the midline is consistent with the view that there is an abnormal attraction for them to the right of the display. One further manifestation of this rightward bias, according to the Kinsbourne view, is that patients should find it more difficult to search in a contralesional direction than in an ipsilesional one. Furthermore, one might predict that this effect would interact with current fixation location such that moving one's eyes leftward would become even less probable as the current fixation was further over to the left. Data suggesting that the attentional deficit is subject to this pattern are provided by Arguin and Bub [2], who showed that their subject with a parietal lesion was more impaired at directing shifts of attention contralesionally and that this was more so when the targets appeared in the contralesional than in the ipsilesional visual hemifield (also see [54]). In contrast, Karnath *et al.* [37] found no difference in the percentage, amplitude and duration of saccades directed contralesionally versus ipsilesionally. However, it is possible that reliable differences do exist but were simply obscured because the latter analysis compared contra- and ipsilesional saccades from a single point of fixation, but the exact location of that fixation was not classified differently according to its left–right position. Thus, to determine whether there is a difference in leftward versus rightward saccades and whether this differs across the quartile bands, we calculated the number of leftward and rightward saccades in each band and normalized the data over the total number of saccades in that quartile.

An analysis of variance with one between-group factor (group) and two within-group factors (quartile of current fixation, direction of saccade) was performed. The proportion of leftward saccades for each of the three groups as a function of band is plotted in Fig. 9. The rightward saccades are simply the reciprocals and hence are not plotted. There was no difference in the overall proportion of leftward versus rightward saccades across the three groups [$F(1,2)=2.9$, $P>0.5$], no difference between the quartiles [$F(3,6)=1.0$, $P>0.1$] nor between the groups themselves [$F(2,19)=0.2$, $P>0.5$]. There was, however,

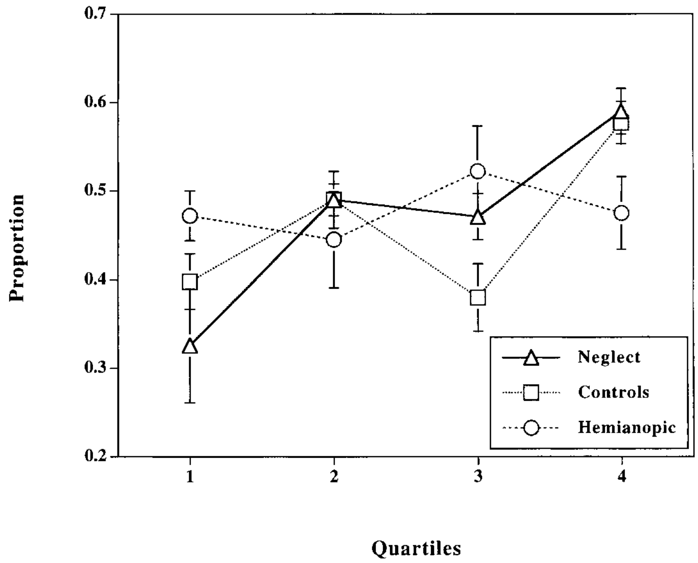

Fig. 9. Proportion of leftward saccades for the three groups as a function of starting quartile.

a significant interaction between groups, quartiles and direction of saccades [$F(6,57)=2.3$, $P<0.05$]. Of most interest in such a task is the direction of saccades from the left and right boundaries of the board. As expected in a strategic search of this sort, in the normal subjects there are fewer left- than right-sided saccades from the far-left quartile and more left- than right-sided saccades from the far-right quartile, rendering the search systematic and controlled.

The hemianopic patients do not show this pattern as strongly and, in fact, produce approximately an equivalent proportion of leftward and rightward saccades in each band. Their compensatory behavior appears to be modulating the more normal, systematic search. Particularly interesting is the interaction in the neglect patients' data showing that, notwithstanding the paucity of left-sided fixations and the concomitant increase in right-sided fixations (which are normalized in this analysis), they too are subject to some of the constraints of the task. In the far-left quartile, they make a similar proportion of leftward saccades as the normal group and are constrained by the left boundary of the search board. They are also constrained by the right boundary and make an equivalent proportion of left-sided saccades from the far-right as do the normal subjects.

General discussion

The primary goal of this study was to examine the distribution of fixations made by neglect patients in a visual search task involving a complex display. Because the pattern of eye movements is often taken as a robust and transparent index of the distribution of attention [19, 27, 44, 45], we might gain insight into the nature of the attentional deficit underlying the visuospatial behavior of these patients through a detailed oculographic analysis. While deficits in eye movement pattern have been documented previously in patients with brain damage and visuospatial deficits (e.g., [9, 16, 20, 30]), there has been little consideration of what gives rise to the observed deficit. To this end, we compared the behavioral report and the eye movement performance of normal subjects, hemianopic patients without neglect and a relatively large group of patients with hemispatial neglect during search for a predefined target in a random visual search display. A comprehensive analysis of the eye movement pattern was undertaken, including both spatial and temporal indices. Importantly, on the spatial indices, because of the layout of the search board, we were able to measure performance as a function of horizontal space from extreme left to extreme right of the display and to plot the frequency of eye movements at a fine scale of analysis.

Before turning to the neglect patients, we briefly summarize the data from the normal and hemianopic groups. The group of normal controls showed no observable bias in their visual exploration, and there were no obvious spatial asymmetries in their performance aside from the expected tendency to start the search on the upper left of the display and to be constrained to move rightwards from the left end of the display and leftward from the right end. The pattern displayed by the hemianopic patients revealed an attempt to compensate for their left-sided field defect. This is reflected in the higher proportion of fixations and longer durations in the far-left quartile band and the tendency to look even beyond the boundaries of the left boundary of the board. These findings conform well with the data reported previously for hemianopic patients on similar types of tasks [30, 51, 67].

As expected, the behavioral data reflected more omissions of targets for the neglect group than for the other two groups. Across a range of oculomotor variables, the neglect patients also showed a very different pattern to those of the normal and hemianopic groups. These differences hold up even when the data are normalized for the relative differences in the absolute number of fixations per quartile band and also when the data are analysed for each patient individually. The most striking feature of the neglect performance is that the patients show a steep gradient in their eye movement patterns: as the bands progress leftward, they make significantly fewer fixations, spend less time searching and make fewer leftward saccades (subject to the constraints of the task). Furthermore, on the far-right of the display, they make more fixations and spend longer inspecting the display than do the normal subjects, although they show the same proportion of leftward saccades from this far-right band as the normal subjects (presumably because of their sensitivity to the right boundary of the board). Finally, a further indication of rightward bias comes from the finding that the neglect patients initiate their search to the right of the midline of the display.

One question that arises is whether the pattern observed in the neglect patients is truly a function of neglect. All nine patients have some form of concomitant field defect, and an alternative explanation for the reduction in saccades and search time on the left is that this is simply the manifestation of the field defect and is not attributable to the neglect *per se*. In fact, it is sometimes difficult to disentangle the contribution of neglect from that of a field defect under standard testing conditions [64]. The inclusion of the hemianopic control group in this study allows us to adjudicate between these alternative interpretations. Whereas the patients with field defects compensate and look towards their contralesional blind side with even greater frequency than normal subjects, patients with left-sided neglect make significantly fewer fixations than normal subjects on the contralesional side. These findings suggest then that it is the neglect *per se* rather than the field defect that is giving rise to the observed pattern of behavior. A remaining issue, however, is whether there is any contribution of the field defect to the performance of the neglect patients or, in other words, whether there might be an interaction between neglect and the presence of a field defect. Several recent studies have argued that patients with neglect and contralateral field defects (whether partial or more complete) perform no differently from neglect patients without sensory loss on free vision tasks [29] and that, from a clinical point of view, neglect is not exacerbated by an accompanying field defect [22]. If this is indeed the case, then these data reflect the eye movement pattern specifically and solely associated with hemispatial neglect, and the observed pattern does not arise from the joint contribution of neglect and the field cut. A perhaps less extreme view, however, might admit to a contribution from the field defect, and detailed examination of neglect patients without accompanying field defects would be necessary to resolve this issue definitively.

Having established the differences between the groups of subjects, we can now turn to a more detailed consideration of the neglect pattern. According to the Kinsbourne view of neglect, one would expect to see the two major signatures of neglect: a left-sided reduction and a simultaneous right-sided increase in fixations. These two effects are not obvious correlates or reciprocals of each other—a right-sided increase does not necessarily entail a left-sided reduction nor vice versa. Because there are no limits on search time, and subjects simply indicate to us when they have completed the task, they are at liberty to search for as long as they wish. Both the left reduction and right increase, relative to the normal group, are clearly evident from the pattern of data yielded by the neglect patients. Importantly, the paucity of left-sided fixations and leftward saccades are not simply explained by the presence of a field defect. The eye movement pattern is also not explained by a basic oculomotor deficit, since the neglect patients can move their eyes to the left as reflected in the calibration procedure and in the task itself. This pattern is also specific to the left–right spatial dimension, as the top–bottom eye movement analysis shows equivalent performance across all three groups.

Rather, these findings appear to be a central manifestation of the neglect deficit.

Thus, the characteristic gradient of the neglect group with a gradual fall-off in frequency of fixations from right to left supports the notion that the imbalance between the opposing leftward and rightward vectors following right-sided brain damage results in a smooth gradient of attention from right to left. This claim is clearly at odds with the view proposed by Heilman *et al.* [23–25], which predicts a sharp discontinuity between information on the ipsilesional and contralesional sides. Instead, the findings support the claim that, under normal conditions, the two cerebral hemispheres mutually inhibit each other so that a balance is maintained between the two sides. In patients with right hemisphere lesions, the unleashed rightward vector (in the intact left hemisphere) orients attention rightwards. This rightward vector is even stronger than that seen in normal subjects, when it is usually countered by the opposing leftward bias. Further data supporting this gradient view have also been obtained in recent studies using other methodologies, such as neuroimaging [11, 12], studies of split-brain patients [47] and even in experimental manipulations with neurologically intact observers [57].

These findings also show that the distribution of eye movements shown by neglect patients is similar under conditions in which they search for a target in the light and when they search for a target (even if it is nonexistent) in the dark. The findings from the present study are strongly compatible with the data reported by Hornak [28] and Karnath *et al.* [35–37, 39], who measured the eye movement patterns of neglect patients in the dark. There is, however, one observation that requires further consideration across these different studies and that concerns the exact nature of the distribution of eye movements on the extreme right. According to the Kinsbourne view, the rightward hyperattention should peak at the extreme right and fall off gradually from that point. What determines the frame of reference upon which the gradient is superimposed? With respect to what coordinate system(s) are left and right defined? We have assumed that the spatial coordinates or frame of reference are determined by the environment or scene or, in this case, the edges of the visual display [3, 18] and, on this account, the maximum peak of fixations should occur at the extreme right of the board.

Other findings, however, have proposed that a frame of reference defined with respect to the midline of the viewer plays a crucial role in determining the distribution of attention. Thus, information to the right of the body midline is well attended and that to the left is poorly attended. A number of recent studies have demonstrated that neglect patients subjectively perceive their bodies as being oriented towards the ipsilesional right side [35, 39], suggesting that the egocentric midline of the body or trunk is deviated rightwards. Consistent with this view is the finding of Karnath *et al.* [36, 37, 39] that eye movements in neglect patients show the peak of maximum fixations at around 15–20° to the right. In light of this (and some support from their other, related studies), Karnath and colleagues have argued that this peak around 15° of the objective body midline might reflect the center of the subjectively perceived body midline and might be indicative of a horizontal displacement of the egocentric frame to the right. Although detailed statistical analysis is not available, Hornak's neglect subjects also appear to have the highest peak of eye movements somewhere in the 10–15° and 15–20° range on the right. Hornak, however, interpreted this peak as artifactual. Because in his study neglect patients were verbally encouraged to widen the extent of the visual search when they did not look to the left, he argued that this peak might arise from the leftward movement that followed this instruction. As such, according to Hornak, the presence of this peak thus does not challenge the directional bias hypothesis.

A careful examination of our data also reveals the highest peak on the right in the two bands, 15–17° and 17–19°. While the frequency of fixations in these two bands does not differ [$F(1,6)=8$, n.s.], there are significantly more fixations in both of these bands compared to the 19–21° band [15–17° versus 19–21°: $F(1,16)=5.4$, $P<0.05$; 17–19° versus 19–21°: $F(1,16)=4.76$, $P<0.045$]. This drop off in fixations towards the extreme right beyond around 15°, when fine bandwidths are delineated, is consistent with the finding of Karnath *et al.* and may indeed reflect the deviation of the egocentric midsagittal plane in hemispatial neglect. The implications of these findings are that the results are generally compatible with a gradient view in which there is gradual fall-off from a rightward peak in a leftward direction. There is, however, one important qualification: the peak on the right side of the distribution may be determined by additional factors such as the midsagittal plane of the viewer and the frame of reference in which the search space is defined and bounded, and not solely by the boundaries of the visual scene.

One final question that needs to be addressed concerns causality. Neglect may arise because of the paucity of left-sided saccades and fixations. Alternatively, the bias against contralesional eye movements may arise from a fundamental and major attentional deficit. Although, from this study, it is not possible to assign causality and directionality definitively, we favor the latter interpretation and propose that the eye movements serve as the readout or motor output of an impaired visuospatial representation. In the majority of our cases, the lesion implicates the parietal region, which is generally considered to be central to the computation of the spatial representation [10]. Eye movements *per se* are largely governed by areas that are predominantly downstream from parietal areas. This suggests that the gradient of attention in neglect leads to an impoverished representation of visual space. Eye movements that depend on this representation thus inherit the biases and asymmetries, thereby giving rise to a pattern of eye movements that is similar to the fundamental attentional impairment.

Like Walker *et al.* [63], then, we would argue that there is no *a priori* reason that the patients do not look to the left, as they can do so when explicitly instructed (or even when a single stimulus is present on the contralateral side). The failure to move the eyes to the left, then, is not the cause of neglect but is a consequence and central manifestation thereof.

Acknowledgements—This work was supported by a Medical Research Council of Canada grant to MB and SB, MRC Fellowship to JB and an NIMH FIRST award to MB (MH54216). The authors thank Phat Nguyen, Jane Collins, Shemira Murji and Patricia Ebert for help with data collection and analysis and Dr J. Sharpe for his input and support.

References

1. Albert, M. L., A simple test of visual neglect. *Neurology*, 1973, **23,** 658–664.
2. Arguin, M. and Bub, D. N., Modulation of the directional attention deficit in visual neglect by hemispatial factors. *Brain and Cognition*, 1993, **22,** 148–160.
3. Behrmann, M. and Moscovitch, M., Object-centered neglect in patients with unilateral neglect: effects of left–right coordinates of objects. *Journal of Cognitive Neuroscience*, 1994, **6,** 1–16.
4. Bisiach, E., Mental representation in unilateral neglect and related disorders: the Twentieth Bartlett Memorial Lecture. *Quarterly Journal of Experimental Psychology*, 1993, **46A,** 435–461.
5. Bisiach, E. and Vallar, G., *Handbook of Neuropsychology*, Vol. 1, ed. F. Boller and J. Grafman. Elsevier Science Biomedical Division (North-Holland), Amsterdam, 1988, pp. 195–222.
6. Black, S. E., Ebert, P., Leibovitch, F., Szalai, J., Blair, N. and Bondar, J., Recovery in hemispatial neglect. *Neurology*, 1994, **45,** A178.
7. Black, S. E., Vu, B., Martin, D. and Szalai, J. P., Evaluation of a bedside battery for hemispatial neglect in acute stroke. *Journal of Clinical and Experimental Neuropsychology*, 1990, **12,** 102.
8. Chedru, F., Space representation in unilateral spatial neglect. *Journal of Neurology, Neurosurgery and Psychiatry*, 1976, **39,** 1057–1061.
9. Chedru, F., Leblanc, M. and Lhermitte, F., Visual searching in normal and brain-damaged subjects: contribution to the study of unilateral subjects. *Cortex*, 1973, **9,** 94–111.
10. Colby, C., In *Attention and Performance VXI*, ed. T. Inui and J. L. McClelland. MIT Press, Cambridge, MA, 1996, pp. 157–177.
11. Corbetta, M., Miezin, F. M., Shulman, G. L. and Petersen, S. E., A PET study of visusospatial attention. *Journal of Neuroscience*, 1993, **13,** 1202–1226.
12. Corbetta, M., Shulman, G. L., Miezin, F. M. and Petersen, S. E., Superior parietal cortex activation during spatial attention shifts and visual feature conjunction. *Science*, 1995, **270,** 802–805.
13. D'Erme, P., Robertson, I., Bartolomeo, P., Daniele, A. and Gainotti, G., Early rightwards orienting of attention on simple reaction time performance in patients with left-sided neglect. *Neuropsychologia*, 1992, **30,** 989–1000.
14. De Renzi, E., *Disorders of Space Exploration and Cognition*. John Wiley, New York, 1982.
15. Duhamel, J. R., Colby, C. L. and Goldberg, M. E., The updating of representations of visual space in parietal cortex by intended eye movements. *Science*, 1992, **225,** 90–92.
16. Duhamel, J. R., Goldberg, M. E., Fitzgibbons, E. J., Sirigu, A. and Grafman, J., Saccadic dysmetria in a patient with a right frontoparietal lesion: the importance of corollary discharge for accurate spatial behavior. *Brain*, 1992, **115,** 1387–1402.
17. Eglin, M., Robertson, L. C., Knight, R. T. and Brugger, P., Search deficits in neglect patients are dependent on size of the visual scene. *Neuropsychology*, 1994, **8,** 451–463.
18. Farah, M. J., Brunn, J. L., Wong, A. B., Wallace, M. and Carpenter, P., Frames of reference for the allocation of spatial attention: evidence from the neglect syndrome. *Neuropsychologia*, 1990, **28,** 335–347.
19. Gainotti, G., In *Hemispatial Neglect*, ed. I. Robertson and J. C. Marshall. Lawrence Erlbaum, London, 1993, pp. 107–122.
20. Girotti, F., Casazza, M., Musicco, M. and Avanzini, G., Oculomotor disorders in cortical lesions in man: the role of unilateral neglect. *Neuropsychologia*, 1983, **21,** 543–553.
21. Halligan, P. W. and Marshall, J. C., Toward a principled explanation of unilateral neglect. *Cognitive Neuropsychology*, 1994, **11,** 167–206.
22. Halligan, P. W., Marshall, J. C. and Wade, D. T., Do visual field deficits exacerbate visuo-spatial neglect? *Journal of Neurology, Neurosurgery and Psychiatry*, 1990, **53,** 487–491.
23. Heilman, K. M., In *Clinical Neuropsychology*, ed. K. M. Heilman and E. Valenstein. Oxford University Press, New York, 1979, pp. 268–307.
24. Heilman, K. M., Bowers, D., Valenstein, E. and Watson, R. T., In *Neurophysiological and Neuropsychological Aspects of Spatial Neglect*, ed. M. Jeannerod. North-Holland, Amsterdam, 1987, pp. 115–150.
25. Heilman, K. M. and Watson, R. T., In *Advances in Neurology*, Vol. 18: *Hemi-inattention and Hemispheric Specialization*, ed. E. A. Weinstein and R. P. Friedland. Raven Press, New York, 1977, pp. 93–105.
26. Heilman, K., Watson, R. T. and Valenstein, E., In *Clinical Neuropsychology*, ed. K. M. Heilman and E. Valenstein. Oxford University Press, New York, 1985, pp. 243–293.
27. Hoffman, J., In *Attention*, ed. H. Pashler. University College Press, London, in press.
28. Hornak, J., Ocular exploration in the dark by patients with visual neglect. *Neuropsychologia*, 1992, **30,** 547–552.
29. Hornak, J., Perceptual completion in patients with drawing neglect: eye-movement and tachistoscopic investigations. *Neuropsychologia*, 1995, **33,** 305–325.
30. Ishiai, S., Furukawa, T. and Tsukagoshi, H., Eye-fixation patterns in homonumous hemianopia and unilateral spatial neglect. *Neuropsychologia*, 1987, **25,** 675–679.
31. Ishiai, S., Furukawa, T. and Tsukagoshi, H., Visuospatial processes of line bisection and the mechanisms underlying spatial neglect. *Brain*, 1989, **112,** 1485–1502.

32. Ishiai, S., Sugushita, M., Mitani, K. and Ishizawa, M., Leftward search in left unilateral spatial neglect. *Journal of Neurology, Neurosurgery and Psychiatry*, 1992, **55,** 40–44.
33. Jahnke, M. T., Denzler, P., Liebelt, B., Reichert, H. and Mauritz, K. H., Eye movements and fixation characteristics in perception of stationary scenes: normal subjects as compared with patients with visual neglect or hemianopia. *European Journal of Neurology*, 1995, **2,** 275–295.
34. Johnston, C. W. and Diller, L., Exploratory eye movements and visual hemi-neglect. *Journal of Clinical and Experimental Neuropsychology*, 1986, **8,** 93–101.
35. Karnath, H. O., In *Spatial Neglect: Position Papers on Theory and Practice*, ed. P. W. Halligan and J. C. Marshall. Lawrence Erlbaum, Hove, U.K., 1994, pp. 147–150.
36. Karnath, H. O., Spatial limitations of eye movements during ocular exploration of simple line drawings in neglect syndrome. *Cortex*, 1994, **30,** 319–330.
37. Karnath, H. O. and Fetter, M., Ocular space exploration in the dark and its relation to subjective and objective body orientation in neglect patients with parietal lesions. *Neuropsychologia*, 1995, **33,** 371–377.
38. Karnath, H. O., Fetter, M. and Dichgans, J., Ocular exploration of space as a function of neck proprioceptive and vestibular input—observations in normal subjects and patients with spatial neglect after parietal lesions. *Experimental Brain Research*, 1996, **109,** 333–342.
39. Karnath, H. O. and Huber, W., Abnormal eye movement behaviour during text reading in neglect syndrome: a case study. *Neuropsychologia*, 1992, **30,** 593–598.
40. Kinsbourne, M., A model for the mechanism of unilateral neglect of space. *Transactions of the American Neurological Society*, 1970, **95,** 143–146.
41. Kinsbourne, M., In *Neurophysiological and Neuropsychological Aspects of Spatial Neglect*, ed. M. Jeannerod. North-Holland, Amsterdam, 1987, pp. 69–86.
42. Kinsbourne, M., In *Unilateral Neglect: Clinical and Experimental Studies*, ed. I. H. Robertson and J. C. Marshall. Lawrence Erlbaum, Hove, U.K., 1993, pp. 63–86.
43. Klein, R., Kingstone, A. and Pontefract, A., In *Eye Movements and Visual Cognition*, ed. K. Rayner. Springer, New York, 1992, pp. 46–65.
44. Kowler, E., Anderson, E., Dosher, B. and Blaser, E., The role of attention in the programming of saccades. *Vision Research*, 1995, **35,** 1897–1916.
45. Kustov, A. A. and Robinson, D. L., Shared neural control of attentional shifts and eye movements. *Nature*, 1996, **384,** 74–77.
46. Làdavas, E., Selective spatial attention in patients with visual extinction. *Brain*, 1990, **113,** 1527–1538.
47. Làdavas, E., Pesce, M. D., Mangun, G. R. and Gazzaniga, M., Variations in attentional bias of the disconnected cerebral hemispheres. *Cognitive Neuropsychology*, 1994, **11,** 57–74.
48. Làdavas, E., Zeloni, G., Zaccara, G. and Gangemi, P., Eye movements and orienting of attention in patients with visual neglect. *Journal of Cognitive Neuroscience*, 1997, **9,** 67–74.
49. Mackworth, N. H. and Morandi, A. J., The gaze selects informative details within pictures. *Perception and Psychophysics*, 1967, **2,** 547–552.
50. Meienberg, O., Harrer, M. and Wehren, C., Oculographic diagnosis of hemineglect in patients with homonymous hemianopias. *Journal of Neurology*, 1986, **233,** 97–101.
51. Meienberg, O., Zangemeister, W. H., Rosenberg, M., Hoyt, W. and Stark, L., Saccadic eye movement strategies in patients with homonymous hemianopia. *Annals of Neurology*, 1981, **9,** 537–544.
52. Mesulam, M. M., A cortical network for directed attention and unilateral neglect. *Annals of Neurology*, 1981, **10,** 309–325.
53. Mesulam, M. M., *Principles of Behavioral Neurology*. F. A. Davis, U.S.A., 1985.
54. Posner, M. I., Walker, J. A., Friedrich, F. J. and Rafal, R. D., How do the parietal lobes direct covert attention? *Neuropsychologia*, 1987, **25,** 135–145.
55. Rapszak, S., Cimino, C. R. and Heilman, K. M., Altitudinal neglect. *Neurology*, 1988, **38,** 178–182.
56. Rayner, K. and Pollatsek, A., *The Psychology of Reading*. Prentice Hall, Englewood Cliffs, NJ, 1989.
57. Reuter-Lorenz, P., Kinsbourne, M. and Moscovitch, M., Hemispheric control of spatial attention. *Brain and Cognition*, 1990, **12,** 240–266.
58. Riddoch, M. J. and Humphreys, G. W., The effect of cueing on unilateral neglect. *Neuropsychologia*, 1983, **21,** 589–599.
59. Rizzo, M. and Hurtig, R., Looking but not seeing: attention, perception and eye movements in simultanagnosia. *Neurology*, 1987, **37,** 1642–1648.
60. Shelton, P. A., Bowers, D. and Heilman, K. M., Peripersonal and vertical neglect. *Brain*, 1990, **113,** 191–205.
61. Talairach, J. and Tournoux, P., *Co-planar Stereotaxic Atlas of the Human Brain*. George Thieme, New York, 1988.
62. Walker, R. and Findlay, J., Saccadic eye movement programming in unilateral neglect. *Neuropsychologia*, 1996, **34,** 493–508.
63. Walker, R., Findlay, J. M., Young, A. W. and Welch, J., Disentangling neglect and hemianopia. *Neuropsychologia*, 1991, **29,** 1019–1027.
64. Walker, R., Findlay, J. M., Young, A. W. and Lincoln, N. B., Saccadic eye movements in object-based neglect. *Cognitive Neuropsychology*, 1996, **13,** 569–615.
65. Williams, D., Reingold, E., Moscovitch, M. and Behrmann, M., Patterns of eye movement during parallel and serial visual search tasks. *Canadian Journal of Experimental Psychology*, 1997, in press.
66. Zelinsky, G. and Sheinberg, D. L., Eye movements during parallel-serial visual search. *Journal of Experimental Psychology: Human Perception and Performance*, 1997, **23,** 244–262.
67. Zihl, J., Visual scanning behavior in patients with homonymous hemianopia. *Neuropsychologia*, 1995, **33,** 287–303.