Patients with hemianopic alexia adopt an inefficient eye movement strategy when reading text

Scott A. McDonald,[1] Galina Spitsyna,[2,3] Richard C. Shillcock,[1] Richard J. S. Wise[2,3] and Alexander P. Leff[2,3]

[1]Department of Psychology, University of Edinburgh, Edinburgh, [2]Department of Clinical Neurosciences, Royal Free Hospital and University College Medical School and [3]MRC Clinical Sciences Centre and Division of Neuroscience, Faculty of Medicine, Imperial College, Hammersmith Hospital, Du Cane Road, London, UK

Correspondence to: Dr Alexander Leff, Department of Clinical Neurosciences, Royal Free Hospital and University College Medical School, London NW3 2QG, UK
E-mail: alexander.leff@imperial.ac.uk

Patients with an acquired homonymous hemianopia often adapt over a period of a few months to compensate for some of the impairments caused by their visual field defect. Changes in their eye movement patterns have been demonstrated as performance on visual tasks improves with time; however, these patients often complain of persistent text reading problems. Using a video-based eye-movement tracking system, we investigated the text reading behaviour of patients with established hemianopic alexia (>6 months post deficit), a condition affecting left-to-right readers, with a homonymous field defect that encroaches into their right foveal/parafoveal visual field. Word-based analyses of text reading are standard in experiments involving normal readers, but this is the first time these methods have been extended to patients with hemianopic alexia. Using this method, we compared the patients' reading scanpaths to those generated by normal controls reading the same passages, and a random model generated by matching the patients' eye movement data to random permutations of the text they read. We demonstrate that patients adopt an inefficient reading strategy, fixating to the left of the preferred viewing location of words of four letters and longer. Fixating to the left of the normal preferred viewing location not only results in less of the fixated word being processed by the language system; ensuing fixations are also more likely to land within the same word (a refixation). It is this refixation rate that is the main factor in slowing reading times in these patients. Our data suggests that patients are able to extract some useful visual information from text to aid the planning of reading scanpaths as their behaviour differs critically from the random model. Potential reasons for this patient group failing to produce an effective reading strategy are discussed.

Introduction

Word identification during reading is almost completely dependent on the high acuity afforded by central (foveal) vision, which extends 1° either side of fixation (Rayner and Bertera, 1979). In parallel with the processes involved in word identification, readers also utilize visual information in parafoveal vision to help plan forward reading saccades so that ensuing words are foveated at their optimum viewing location. The eye movement behaviour of readers reading text printed from left-to-right has been shown to be dependent on an asymmetrical attentional window that extends to the right

of fixation (Rayner *et al.*, 1980). This attentional window has been shown to be 'plastic' and not 'hard-wired' in a series of experiments with skilled bilingual subjects reading opposing unidirectional texts (e.g. Hebrew and English) (Pollatsek *et al.*, 1981). Although normal reading fixations range between ∼100 and 400 ms, averaging at ∼200 ms, experimental manipulations of viewing time have demonstrated that the visual information necessary for reading can be acquired during the first 50 ms of a fixation, leading to the conclusion that the remainder of the fixation is devoted to

higher order processing and planning the next saccade (Rayner *et al.*, 1981, 2003).

Text reading fluency is particularly impaired when essential visual information cannot be obtained from the right visual field (RVF) due to an acquired hemianopia, because word identification is difficult if only the initial letters can be seen, and fixations cannot be precisely directed onto as-yet unseen words (Zihl, 1995; De Luca *et al.*, 1996; Leff *et al.*, 2000). To date, no studies of eye movements in patients with visual field defects have reported detailed analyses of reading performance at the level of the word, yet a word-based model of eye guidance underpins the vast majority of contemporary studies of eye movement control in normal readers (Rayner, 1998). Incorporated into this model is the observation that the distribution of initial fixation positions for all but the shortest words shows a preferred viewing location slightly to the left of the word-centre (Rayner, 1979). We wished to investigate whether patients with hemianopic alexia compensated for this presumably serious impediment to reading, hypothesizing that if the system for guiding reading saccades could adopt a compensatory strategy then initial fixations on a word would be made so that, on average, more of the word would fall into the intact left visual field (LVF) and be initially projected to the less compromised right hemisphere; i.e. patients would fixate to the right, compared with normal subjects.

As well as investigating the preferred viewing locations of hemianopic alexic (HA) patients, we wanted to examine the factors that influenced the planning of HA reading scanpaths. Leff *et al.* (2000) described the performance of three patients with macular splitting hemianopia in the task of reading arrays of words. Their ratio of fixations to number of words was about three times as large as observed in normal readers. It was suggested that progressive reading saccades generated by HAs are of the 'hit-or-miss' variety; because of the absence of visual information in the RVF, saccades cannot be aimed towards an upcoming word. De Luca *et al.* (1996) had previously arrived at a similar conclusion, arguing that when parafoveal information cannot be obtained, readers are '. . . left with the sole option of global control and proceed with small and regularly spaced saccades' (De Luca *et al.*, 1996). Global control relates to the strategy of making short saccades through the text at a predetermined rate, i.e. the reading scanpath is unaffected by the text itself. Normal readers also exhibit considerable difficulty when letter information in the RVF is degraded or made unavailable using a gaze-contingent display paradigm (McConkie and Rayner, 1975; Rayner and Bertera, 1979). Accordingly, a second goal of this study was to address whether reading scanpaths made by HAs were consistent with a 'hit-or-miss' description. In order to test this hypothesis we compared the patterns in patients' eye movement data with those predicted by a random-placement model. If HA's planning of progressive saccades is under global control then their reading eye movement patterns should be indistinguishable from those generated by the random-placement model.

The main comparisons we made in these experiments were between the reading eye movements of the HA group and those of (i) normal readers (N), who exhibit a strong association between underlying text and ensuing reading fixations, and (ii) a model (RAND) where fixations were artificially dissociated from underlying text, resulting in a random association between words and fixation locations.

Methods
Subjects
Eighteen patients with a right-sided homonymous hemianopia that interfered with reading participated in this study (median age: 57; range: 24–73). In the majority of cases the hemianopia was secondary to a posterior cerebral artery territory stroke, but head injury and tumours were among the causative lesions (Table 1). Patients were recruited into an ongoing, single-blinded, crossover, behavioural, rehabilitation study aimed at improving their reading speeds. Data were collected on (i) a battery of neuropsychometric tests (not reported here); (ii) single word reading speeds (using a voice key activated system); and (iii) text reading speeds [reading Neale passages aloud (Neale, 1989)]. Single word reading speeds cannot be simply extrapolated from text reading speeds as they were measured using a voice key system that measures time from stimulus presentation to initiation of vocalization. Text reading times were measured by timing the subject's oral reading of the Neale passages and thus include the time required for articulation. Patients also underwent tests of visual perimetry using both static (Humphrey) and dynamic (Goldmann) techniques, had recordings of their eye-movements made while reading specific passages of tailor-made text (*see* below) and had an MRI brain scan.

Ten unimpaired control participants (median age: 49 years; range 24–75 years; six males and four females) were also tested.

Materials and apparatus
Materials consisted of 10 short (∼50 words each) text passages extracted from newspaper journalism (*see* Appendix for example). Passages were displayed on a 22 in monitor, and each passage occupied at most nine lines of the display. Screen resolution was 1024 × 768 pixels, and text was rendered in 36-point Arial font as black on a white background. Viewing distance was between 60 and 80 cm; at this distance an average-width letter subtended 0.8° of visual angle.

Each patient read silently 3 of the 10 passages while his or her eye movements were monitored, as these passages were designed to be used in different combinations at set time points in their longitudinal treatment trial. Data presented here were from pre-treatment recordings only. Comprehension was tested after reading each text by asking the participants to reiterate its content. The control subjects each read all 10 passages.

Recording of eye movements
Eye movements were recorded with an SR EyeLink II video-based head-mounted eyetracking system. Viewing was binocular and the position of both eyes was sampled at 500 Hz. After fitting the headband, the participant's eye position was calibrated using a 9-point grid. Drift correction was performed before each passage was displayed and calibration was repeated when necessary throughout the course of the experiment.

Table 1 Clinical details and behavioural assessments

Case	Sex	Age at onset	Time since symptom onset years (months)	Cause of hemianopia	Right visual field defect	Degrees of sparing of right visual field	Single word reading speeds for 3 letter words (s)	Text reading aloud (wpm)
1	M	51	2 (1)	Haemorrhage	HH	2	0.98	54
2	M	61	1 (1)	Stroke	HH	0	1.36	58
3	M	24	14	Haemorrhage	HH	2	0.9	58
4	M	53	1 (3)	Stroke	HH	2	1.09	59
5	M	39	2 (1)	Stroke	UQ	0	1.03	63
6	M	62	1 (11)	Stroke	HH	0	0.82	71
7	M	67	(9)	Stroke	LQ	2	0.86	89
8	F	34	2 (6)	Brain injury	HH	2	0.8	86
9	M	57	(6)	Stroke	HH	0	1	83
10	F	67	2 (3)	Stroke	LQ	0	1.06	86
11	M	73	5 (2)	Stroke	HH	2	0.82	95
12	F	71	(3)	Stroke	HH	0	0.78	98
13	M	66	1	Stroke	UQ	0	1.22	99
14	M	69	1 (3)	Stroke	UQ	0	0.82	101
15	F	52	(9)	Tumour	HH	0	0.99	108
16	F	64	2 (2)	Haemorrhage	UQ	0	0.98	109
17	M	59	2 (2)	Stroke	HH	2	0.95	110
18	F	55	3 (11)	Tumour	HH	0	0.76	113

All fields are homonymous. HH = hemianopia; UQ = upper quadranopia; LQ = lower quadranopia.

Data analysis

Eye movement recording and analysis of fixation sites

Fixation position and duration data from the left eye only were used, except for one patient (Case 15) for whom recording was monocular from the right eye. A preliminary stage of data selection preceded our analyses of the two groups' eye movement patterns. Data for the first word on the line and the word receiving the first fixation of the line (if not the first word) were eliminated from consideration. Analyses were conducted using both *first-pass* only reading data—data associated with the initial fixation(s) made on a given word, until the eyes exit the word, either to the left or to the right— and *all-passes* data, which included subsequent re-readings of the text.

All reported values are normalized for the screen width needed to render words of the same letter-length in a proportional font and are computed as the proportion through a word-box, that is, measured from the left edge of an invisible box drawn around the word and the preceding blank space. All our spatial measurements are based on this letter-based method rather than absolute visual angle as different words with the same number of letters will be different widths depending on their constituent letters (e.g. ill versus odd) (Morrison and Rayner, 1981). Average word-box widths for the 3–7 letter words in the materials were 93, 120, 142, 171 and 198 pixels, respectively, and the average letter width was 25 pixels.

A randomization approach was applied to estimate the eye movement behaviour expected under assumptions of 'hit-or-miss' saccade planning (McDonald and Shillcock, 2005). This procedure involved mapping the patients' behavioural data (the recorded sequences of saccades and fixations) to random permutations of the same text passages that they actually read. The random mapping was performed as follows. First, the order of the words in each passage was randomized transforming the passage into a random list of words. Line breaks were imposed on this list using an algorithm that produced roughly the same line lengths present in the original passage. Second, the fixation sequence (*x*- and *y*-coordinates of the fixation position, in pixels) recorded from the patient while reading the original text was mapped to the randomized version of the same text. The resulting mapping simulates the situation where there is no dependence between eye movements and the material being read, and permits the random-placement data to be analysed using exactly the same methods as used for the original data.

Four randomized versions of the original 10 passages were created providing a total of 212 distinct mappings for the hemianopic group (12 mappings each for 17 patients; eight for the single patient who read two passages only).

Perimetry

Static fields were measured using the automated Humphrey field analyser II (Carl Zeiss Group, California) of the central 10° of vision (central 10-2 threshold test), and kinetic perimetry was performed with the standard Goldmann perimeter (Haag Streit, Köniz, Switzerland). The Humphrey analysis produces five data points for the 10° either side of fixation. The points are evenly spaced at 2° intervals but offset so that the first point is 1° of eccentricity, the second at 3° etc. We deemed a point in the visual field to be defective (not useful for reading) if the threshold (in decibels) was less than half that recorded at the equivalent mirror point in the good (left) field. If the first point was defective then the patient was classified as having 0° of sparing; if the first point passed but the second failed then they were classified as having 2° of sparing (a value midway between the two defining points). All the patients in this study fell into one of these two groups. All patients had fields that were homonymous, but as each eye was tested separately discrepancies arose between homonymous points in the visual field, especially at the edge of the deficit. Where there was discrepancy between a given homonymous point from the recordings from both eyes, we selected the result for the 'best' eye. Eleven patients were classified as exhibiting 0° of sparing and seven as having 2°. This variable was entered into the analyses of variance (ANOVAs) as a between-subjects factor. Results involving amount of sparing are only reported if a reliable ($P < 0.05$) main effect was obtained, or if sparing interacted with another factor.

Results

The reading behaviour of the HA group, as judged by their eye-movement recordings, differs from both the normal control subjects (N) and the random model generated from the patients' own eye movement recordings (RAND). The comparisons between HA and N data will be dealt with first followed by the comparisons between HA and RAND data.

HA versus N

Consistent with previous reports (Zihl, 1995; De Luca *et al.*, 1996; Leff *et al.*, 2000), HAs' eye movements differed from those of normal readers with respect to both temporal and spatial measures. The distinguishing characteristics of the HA data were a greater number of fixations, with excess saccades being of both the progressive and regressive type. There was a significant difference between N and HA groups for progressive saccadic amplitude, computed from the all-passes data [mean amplitudes of 180 and 102 pixels, respectively; corresponding to 7.2 and 4.1 average-width letter spaces, $F(1,26) = 63.48$, $P < 0.001$], and also for regressive saccadic amplitudes [mean amplitudes of 142 and 94 pixels, respectively, corresponding to 5.7 and 3.8 average-width letters, $F(1,26) = 5.72$, $P < 0.05$]. Compared with the N group, the HA group produced a larger number of fixations on average [219 fixations/100 words versus 85/100 words, $F(1,26) = 49.90$, $P < 0.001$], and their mean fixation duration was longer [222 versus 174 ms, $F(1,26) = 22.68$, $P < 0.001$]. [Although it is the difference in mean fixation duration between the two groups that is of primary interest, we note that the values for both the patients and the control subjects are substantially smaller than values typically reported in other reading eye movement studies (Rayner, 1998). The current values may be smaller than usual because letter visibility was quite high due to the large visual angle subtended by an average letter ($0.8°$) in our study. In support of this suggestion, O'Regan *et al.* (1983) found that mean fixation duration decreased as viewing distance decreased, with which visibility would presumably co-vary.]

Spatial characteristics
Initial landing position

The data for the spatial measurements are presented in Table 2 for words of three through seven letters in length. The initial landing position (ILP) is shown in the first column. The N group fixated just to the left of centre of the word, regardless of its length, while the HA group consistently landed to the left of the N group's ILP for words of four letters or more; this effect was more pronounced the greater the word length (WL): $F(1,17) = 22.41$; $P < 0.001$. Between-group contrasts in mean landing position were reliably different for the four-through seven-letter words ($F > 5.97$, $P < 0.03$) but not for the three-letter words: $F(1,26) < 1$. Figure 1 illustrates a representative difference in group means for five-letter words. Figure 2 displays the distributions of the ILP for both groups

Table 2 Spatial eye movement measures, comparing hemianopic (HA) and normal (N) groups, computed separately for words of three through seven letters in length. Values are means of individual readers' means

WL	LP		SkipP		RefixP		N	
	HA	N	HA	N	HA	N	HA	N
3	0.49 (1.7)	0.48 (1.7)	0.22	0.63	0.22	0.06	258	239
4	0.42 (1.8)	0.50 (2.2)	0.11	0.39	0.40	0.09	314	351
5	0.39 (2.1)	0.48 (2.5)	0.05	0.30	0.53	0.14	210	281
6	0.34 (2.1)	0.43 (2.7)	0.02	0.16	0.64	0.21	162	245
7	0.28 (2.1)	0.45 (3.3)	0.03	0.11	0.71	0.22	216	350

N is the total number of first-pass fixated cases. WL = word length (letters); LP = normalized landing position, in proportion through word, including the space before the word (landing position in estimated letter position is provided in parentheses); SkipP = proportion of cases where the eyes initially skip over the word; RefixP = proportion of cases where a fixated word receives more than one fixation.
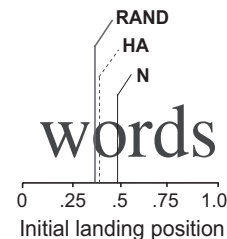

Fig. 1 Mean ILP (in proportion into the word) for five-letter words, comparing N, HA and RAND groups.

and the RAND model. HAs clearly fixate more often to the left of where Ns do for words four to seven letters long.

Refixation rates

Mean refixation rates (the proportion of cases where the saccade following the initial fixation on a word lands on the same word) ranged from a low of 0.06, for the control group's three-letter word data, to 0.71, for the seven-letter words read by the patients. Both N and HA groups were more likely to make a refixation as WL increased; N: $F(4,36) = 10.90$; $P < 0.001$. HA: $F(4,68) = 37.95$, $P < 0.001$; but the mean refixation rates for the N group were substantially lower than those observed for the HA group [between-groups main effect: $F(1,26) = 51.50$, $P < 0.001$]. There was no effect of visual field sparing on refixation rates: $F(1,16) < 1$. Figure 3 displays refixation proportions as a function of ILP. Although vertically displaced from the N group curves, the HA curves are of roughly the same shape. Both groups were more likely to make a refixation when the first fixation was near the beginning than further into the word, HA: $F(1,17) = 37.09$, $P < 0.001$; N: $F(1,9) = 52.24$, $P < 0.001$.

Skipping rates

Mean skipping rates (the proportion of cases where words of a given length are not directly fixated during first-pass reading)
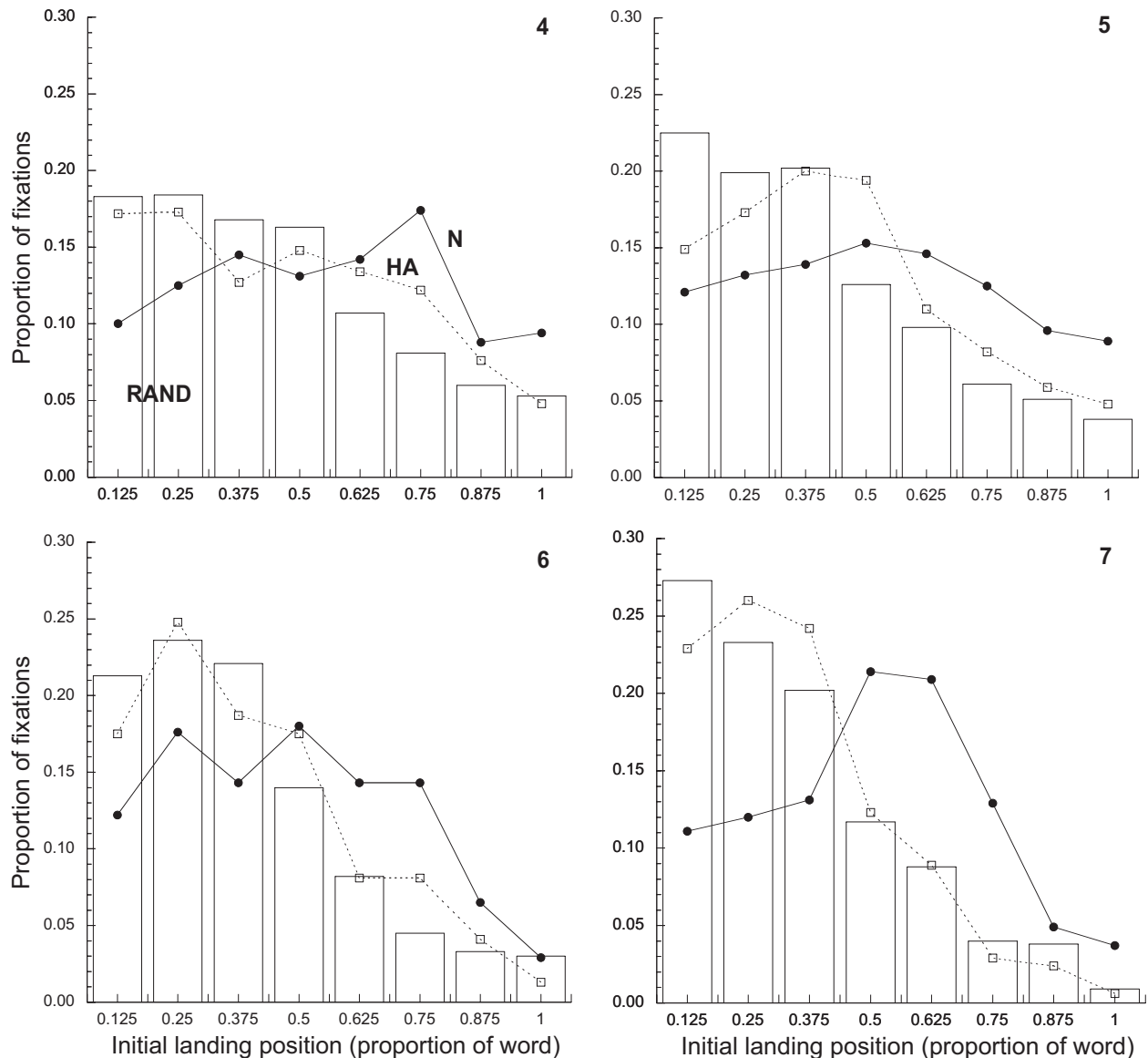
Fig. 2 Distribution of ILPs for the three groups for four-letter (*top left*), five-letter (*top right*), six-letter (*bottom left*) and seven-letter (*bottom right*) words. Open squares = HA, closed circles = N. Bars indicate the values predicted by the random-placement model = RAND. Landing position is the proportion into the word (including the preceding space) divided into eight equal-width bins.

decreased as WL increased for both the N and HA groups for all five words lengths; N: $F(4,36) = 51.74$, $P < 0.001$; HA: $F(4,68) = 30.89$, $P < 0.001$. Both groups were less likely to skip a word as its length increased, but this effect 'bottomed-out' for the HA group at five-letters WL (Bonferroni *post hoc* comparisons, correcting alpha level for multiple comparisons: WL3 was different to all other WLs; WL4 was different to WL3, WL5 and WL7); while the N group continued to show an inverse relationship between skipping rate and WL for the whole range of WLs (*see* Table 2).

Temporal characteristics

Table 3 displays three commonly reported word-based fixation time measures: first fixation duration (FFD), the length of the first fixation made on the word, regardless of whether the word received single or multiple fixations; gaze duration, the summed duration of all first-pass fixations before the eye exits the word; and, total fixation time (TFT), the sum of all fixations made on the word, including those made in second or further inspections of the word.

For both N and HA groups, FFD tended to increase as WL increased, N: $F(4,36) = 9.42$, $P < 0.001$; HA: $F(4,64) = 2.43$, $P = 0.057$; with no reliable Sparing × WL interaction: $F(4,64) = 2.00$, $P = 0.105$. The two other measures also increased as a function of WL, but unlike FFD these measures are confounded by refixation rates which were high for the HA group in general and for the longer words the N group read.

Figure 4 displays mean FFD as a function of landing position. Sufficient data were available only for the
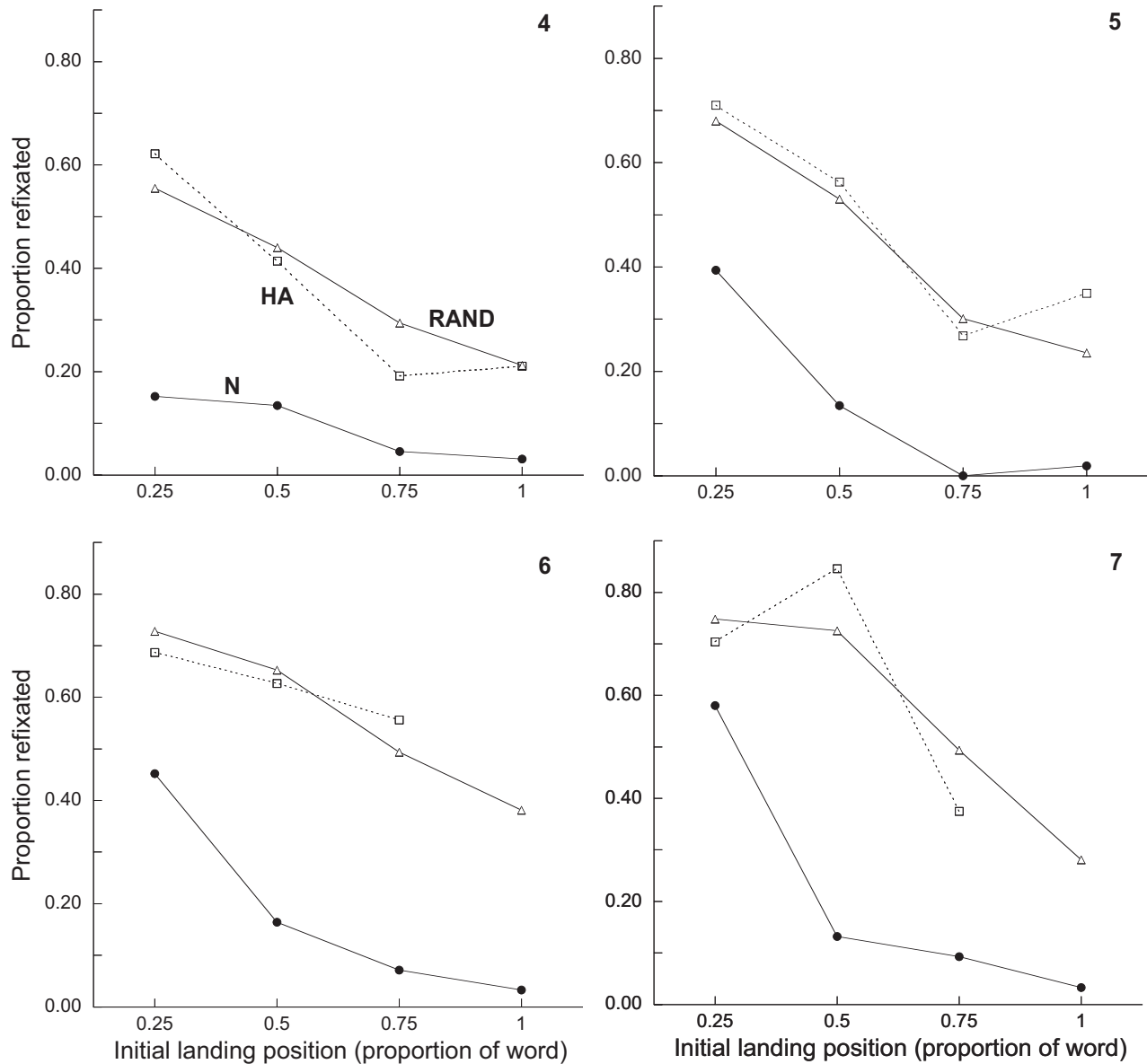
Fig. 3 Probability of making a refixation as a function of ILP (hemianopic readers), for four-letter (*top left*), five-letter (*top right*), six-letter (*bottom left*) and seven-letter (*bottom right*) words. Open squares = HA, closed circles = N, open triangles = RAND. Landing position is the proportion into the word (including the preceding space) divided into four equal-width bins. Points based on fewer than 15 cases are not plotted.

four- and five-letter words to allow a meaningful graphical and statistical evaluation. For the HA group and for both WLs, FFD was shortest at word beginning and maximal when the eye first landed between 50 and 75% through the word. There was a significant effect of fixation position: $F(3,48) = 3.40$, $P < 0.05$; $F(3,48) = 2.98$, $P < 0.05$; for the four- and five-letter words, respectively. The general shape of the HA curves is an inverted U. A trend analysis showed a significant and a marginally significant quadratic component for four- and five-letter words, respectively, $F(1,17) = 4.45$, $P = 0.05$; $F(1,17) = 3.65$, $P = 0.073$; the linear component was not significant at the 0.05 level.

The amount of VF sparing was a significant predictor for the four-letter words, but not the five-letter words, $F(1,16) = 6.51$, $P < 0.05$; $F(1,16) = 1.36$, $P > 0.25$. For the four-letter words, mean FFD for the patients with zero sparing was 43 ms shorter than for the patients with 2° of sparing; however, there was no effect of sparing on refixation rates for four-letter words $F(1,16) < 1$.

The analogous plots produced from the control group's data did not exhibit the pronounced inverted U-shape seen in the HA data, their curves were markedly flat. Furthermore, there was no reliable effect of ILP on fixation duration: $F(3,27) = 2.74$, $P > 0.06$; $F(3,27) = 1.68$, $P > 0.19$, for the four- and five-letter words, respectively.

HA versus RAND

We compared ILP and refixation rate between HA and RAND datasets in order to provide a measure of how dependent the HAs' reading scanpaths were on the text being read. If the two datasets correlated then this would provide evidence that the HA scanpaths are not significantly driven by the underlying text.

Spatial characteristics

The landing position distributions displayed in Fig. 2 are heavily skewed, and indicate that the majority of fixations landed on the first few letters of the word for all three groups. The distributions computed from the RAND data are shifted leftwards of the HA group (*see* Figure 1 for group means for

five-letter words); the mean landing position was leftward for the three-, four- and five-letter words: $F(1,17) = 9.27$, $P < 0.01$; $F(1,17) = 5.06$, $P < 0.05$; $F(1,17) = 4.34$, $P = 0.053$; respectively, but not for the six- and seven-letter words: $F(1,17) = 1.11$, $P > 0.3$; $F(1,17) < 1$; respectively.

Figure 3 plots refixation proportions as a function of ILP, for words of length four through seven letters, for all three groups. The highest refixation rates occurred when the eye landed on the first letter or on the space before the first letter, the lowest rates were observed for fixations near word-centre and further rightwards. Mean refixation rate did not differ between the HA and RAND datasets: $F(1,17) < 1$.

Temporal characteristics

There were no global differences in FFD between HA and RAND groups: $F(1,16) < 1$.

Discussion

Patients with hemianopic alexia produce reading scanpaths which differ from those produced by normal controls both in the temporal and spatial aspects of their constituent fixations. Compared with normal subjects reading text passages, HAs are more likely to make an initial fixation at the start of a word, fixate for longer, refixate a word and are less likely to skip over shorter words. HAs are, however, able to make some use of the limited visual information available to them as their reading behaviour differs critically from that predicted by a random model that dissociates eye movement patterns from the underlying text.
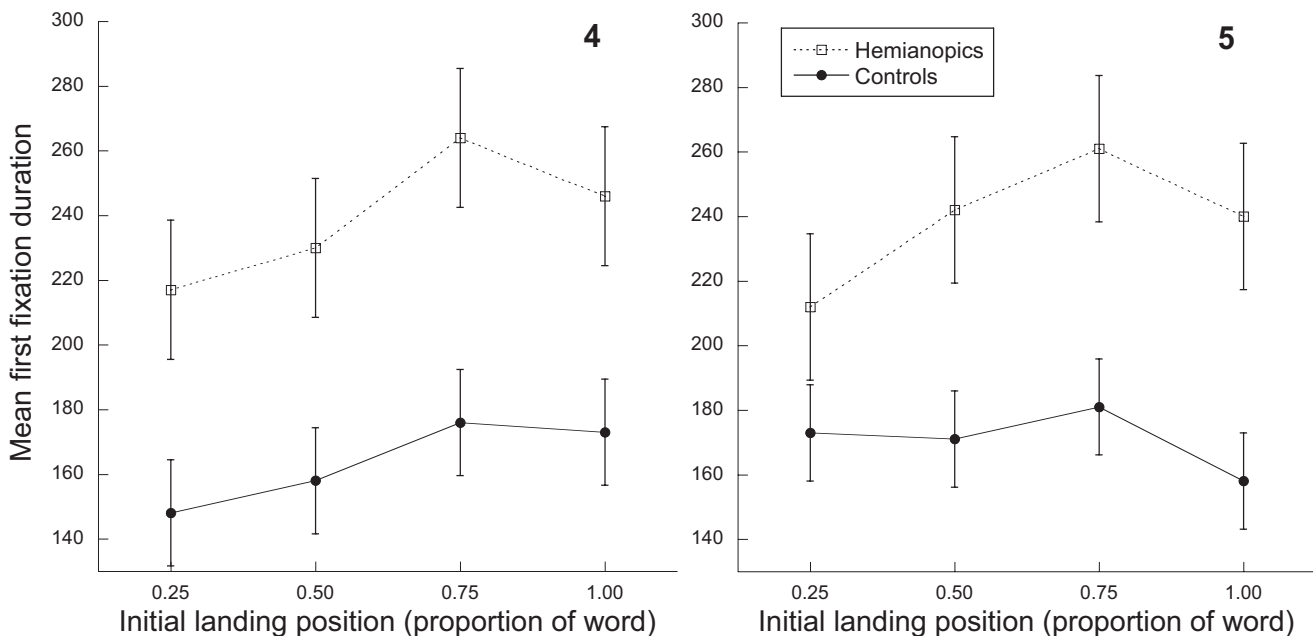
Table 3 Temporal eye movement measures for words of three through seven letters in length, comparing hemianopic (HA) and normal (N) groups. Values are means of individual readers' means

WL	FFD		Gaze		TFT	
	HA	N	HA	N	HA	N
3	232	149	277	157	341	168
4	240	165	358	177	452	187
5	240	173	405	192	517	211
6	223	176	490	204	646	221
7	240	176	529	209	689	225

WL = word length, in letters; FFD = first fixation duration; Gaze = sum of first-pass fixation durations; TFT = total fixation time, all passes through the text.

Fig. 4 Mean FFD (in ms) as a function of ILP, for four-letter (left panel) and five-letter (right panel) words only, comparing the HA and N groups. Landing position is the proportion into the word (including the preceding space) divided into four equal-width bins. Bars indicate within-subject 95% confidence intervals, computed as recommended by Loftus and Masson (1994).

Reading scanpaths have been investigated in patients with different types of 'peripheral' alexia (Behrmann *et al.*, 2001; di Pellegrino *et al.*, 2001–2002; Rayner and Johnson, 2005), including HA; however, this is the first study to provide a word-based analysis of their reading behaviour. Perhaps the most important finding is that the hemianopic readers' initial fixations tended to fall near the beginning of the word in marked contrast to the normal group for whom the preferred viewing location was closer to the word-centre. This finding is not consistent with the development of a compensatory fixation strategy, as only the first one or two letters of the word (falling in the LVF) are perceptible at the mean landing position confounding our initial prediction that the HAs would fix to the right of the normal preferred viewing location, making the most of intact foveal/parafoveal vision to the left of fixation.

Fixating to the left of normal appears to be an inefficient strategy for HA readers because not only are fewer letters of the word seen (the patients' mean initial fixation position, when converted to letter position, was near constant: 1.7, 1.8, 2.1, 2.1 and 2.1, for the three- through seven- letter words, respectively) but the need for further refixations within the word increases the more leftward the initial fixation (Fig. 3). Initial fixations to the right of centre of a word were ∼40 ms longer on average (Fig. 4) for the HA group, but this was more than compensated for by the high chance of not having to make a refixation following this (∼20% compared with 60% for ILPs in the first quarter of the word: Fig. 3).

Because information such as letter identities to the right of fixation and the physical locations of upcoming words cannot be obtained by patients with right-sided hemianopia, De Luca *et al.* (1996) proposed that HAs plan saccades using a 'global control' strategy; short saccades are sent ahead through the text at a predetermined rate. With this strategy, saccades can be described as 'hit-or-miss': fixations may or may not occur at positions in a word where sufficient letter information can be obtained to permit word identification. Our random-placement model provides an estimate of the expected behaviour under such a saccade planning strategy, and the HAs' eye movement patterns showed significant departures from the behaviour predicted by a global control strategy. First, their landing position distributions were shifted rightward compared with the random placement model, indicating that even though essential spatial information cannot be obtained from the RVF saccade planning is not well described as being under global control. Second, evidence that forward saccades do not simply proceed at a predetermined rate is provided by the reliable dependence of FFD on fixation position. This suggests that the HAs are exerting text-relevant control over their reading scanpaths, which could be 'top-down' (context driven), 'bottom-up' (non-linguistic visual factors, perhaps viewed with residual RVF foveal/parafoveal function) or a combination of both. Interestingly, the HAs' dependence of duration on position is stronger than in previous analyses of normal readers, which were based on much more data (Vitu *et al.*, 2001). A global control strategy would

predict only a minimal influence on fixation durations from the location fixated in the word.

We found, like Zihl, that HAs have longer fixation durations. Our patients' FFD were roughly 50% longer than those of the controls, whereas Zihl reported that his patients' fixations were on average 75% longer than normal. This may be due to either slowed word recognition times associated with dominant occipito-temporal damage or the loss of parafoveal vision which would normally allow a 'preview' of upcoming words, and thus shortened fixation times when a previewed word is subsequently fixated (Blanchard *et al.*, 1989). The difference in FFD, large though it is, is not the predominant cause for HAs' slowed reading rates which are characterized by total fixation times of ∼250–300% longer than normal for words longer than four letters in length. The main reason for this is the employment of a laborious scanpath strategy characterized by fixating too far to the left-of-centre of a word which in turn leads to further refixations within the word being the rule rather than the exception.

Our patient group selected itself in the sense that they all had right homonymous field defects and problems with text reading. No patient had more than 2° of sparing. Zihl found that patients with more peripheral parafoveal deficits were slower to read text but this effect dropped off in a non-linear manner with increasingly preserved parafoveal fields. Rayner and Bertera (1979) also demonstrated this non-linear effect, with reading performance improving rapidly once parafoveal masks moved out beyond 2° to the right of fixation (Fig. 2C and D in Rayner and Bertera, 1979). While patients with >2° of sparing may well be slower to read as a result of their visual deficit, the effect may be small enough that the majority of such patients will not seek specialist help. We also failed to demonstrate any meaningful differences between the 0 and 2° sparing groups in any of our analyses. The likeliest explanation is that we did not study enough patients to show the expected relative difference between the two groups. Our subjects varied roughly by a factor of two in their single word and text reading speeds (Table 1). Factors unrelated to degrees of sparing such as premorbid reading ability and variations in the pattern and extent of dominant occipital pathology (amount of damage to white/grey matter regions) may explain this variation.

Poor compensatory strategy?

Although not tested directly in this study, it seems unlikely that the HAs' reading scanpaths simply relate to a generally poor scanning strategy applied to any visual task, as patients with longstanding hemianopia do not produce the same eye movement patterns when viewing photographs or degraded visual images (Pambakian *et al.*, 2000). In their study, Pambakian *et al.* (2000) found that hemianopic patients had longer scanpaths and spent more time scanning their blind fields compared to normals, but they did not differ in terms of the duration of their initial fixation or percentage of refixations, and made only ∼13% more fixations which were of a

shorter, not longer, duration than normals. Hemianopic patients are therefore clearly able to adapt in other areas of visual function (Zangemeister *et al.*, 1995), with some evidence that fixation to the right of normal is part of this process (Ishiai *et al.*, 1987). So why do HA patients exhibit such conservative scanpaths when reading text? We consider three potential reasons for this apparent lack of adaptation, or the adoption of an inefficient strategy.

First, while the asymmetrical reading span may be plastic, few would argue that retinotopic cortical acuity is. As acuity falls off rapidly with eccentricity (Randall *et al.*, 1966), fixing to the right of normal runs the risk of placing the initial portion of the word in low acuity left parafoveal vision, and because the beginnings of English words are more informative than their endings (Pynte, 1996) this strategy could interfere with word recognition and lead to an excess of regressive saccades.

Second, so-called staircase scanpaths appear to be the default strategy for exploring the visual word when it is not possible to predict where the target is likely to be in the blind field (Meienberg *et al.*, 1981). Meienberg *et al.* (1981) found that hemianopic patients would resort to this 'safe but slow' strategy in search paradigms either soon after the deficit was acquired, or for the first few trials of a novel task, or, perhaps most pertinently, if the task they were given was to fix an unpredictable target in their blind field. Normal readers produce staircase scanpaths when reading text, but patients with HA produce an exaggerated staircase pattern with many more steps per line (Zihl, 1995; Upton *et al.*, 2003). Although 'top-down' factors influence reading scanpaths, normal readers often fixate words that can be anticipated. Drieghe *et al.* (2004) demonstrated that four-letter words that were highly predictable from the preceding context were actually skipped less often than two-letter words that were unpredictable; therefore, even if HAs have come to rely on context more than most, contextual factors alone may not be strong enough to overcome the loss of 'bottom-up' visual information.

Finally, there may be a greater neuronal cost in making regressive rather than forward saccades leading the processor to prefer a scanpath strategy with fewer 'expensive' regressions but less effective forward saccades.

The saccadic system appears to 'prefer' undershoots to overshoots, as it takes subjects longer to generate a corrective saccade in the direction opposite to that of the initial saccade compared with one in the same direction (Henson, 1978). This is presumably due to the corrective command having to be issued by cortical regions in the opposite hemisphere (Miller, 1982). A staircase scanpath would therefore require less cortical activity per fixation than a scanpath with multiple regressive saccades, each regression requiring two shifts of visuospatial attention and oculomotor saccadic generation. Overshooting would occur most often when the next word is short. The distribution of WLs in text is heavily skewed; e.g. two- and three-letter words are much more frequent than longer words (Zipf, 1935). In the 458 words comprising

the 10 text passages read by our subjects, the most probable WL was three letters, and words of three letters or fewer represented 36% of the words in the text. A strategy that minimizes the chances of overshooting the relatively common short words would be one that limits how far the next fixation can be sent ahead of the estimated end of the currently fixated word.

Conclusion

We have shown, using a word-based analysis, that the spatial and temporal aspects of HAs' reading attentional window are adversely affected by their hemianopia and attendant dominant occipito-temporal lobe damage. Patients neither resort to a solely bottom-up solution (reading saccades independent of the text: the global control theory) nor do they become over-reliant on top-down processes (over-confident saccades into their blind field based on context); their reading fixations are longer, but the most disabling feature of their reading behaviour is the adoption of an 'exaggerated staircase' strategy, a primitive response usually superseded by other more effective strategies in patients with chronic lesions when attempting other visuomotor tasks. Various parameters such as ILP and frequency of refixations are potential substrates for behavioural rehabilitation techniques aimed at redressing this inefficient oculomotor reading strategy.

References

Behrmann M, Shomstein SS, Black SE, Barton JJ. The eye movements of pure alexic patients during reading and nonreading tasks. Neuropsychologia 2001; 39: 983–1002.

Blanchard HE, Pollatsek A, Rayner K. The acquisition of parafoveal word information in reading. Percept Psychophys 1989; 46: 85–94.

De Luca M, Spinelli D, Zoccolotti P. Eye movement patterns in reading as a function of visual field defects and contrast sensitivity loss. Cortex 1996; 32: 491–502.

di Pellegrino G, Ladavas E, Galletti C. Lexical processes and eye movements in neglect dyslexia. Behav Neurol 2001–2002; 13: 61–74.

Drieghe D, Brysbaert M, Desmet T, De Baecke C. Word skipping in reading: on the interplay of linguistic and visual factors. Eur J Cogn Psychol 2004; 16: 79–103.

Henson DB. Corrective saccades: effects of altering visual feedback. Vision Res 1978; 18: 63–7.

Ishiai S, Furukawa T, Tsukagoshi H. Eye-fixation patterns in homonymous hemianopia and unilateral spatial neglect. Neuropsychologia 1987; 25: 675–9.

Leff AP, Scott SK, Crewes H, Hodgson TL, Cowey A, Howard D, et al. Impaired reading in patients with right hemianopia. Ann Neurol 2000; 47: 171–8.

Loftus GR, Masson MEJ. A proposed confidence interval for use in within-subject designs. Psychon Bull Rev 1994; 1: 476–90.

McConkie G, Rayner K. The span of the effective stimulus during a fixation in reading. Percept Psychophys 1975; 17: 578–86.

McDonald SA, Shillcock RC. Towards an appropriate baseline for measures of eye movement behavior during reading. J Exp Psychol Hum Percept Perform 2005; 31: 584–91.

Meienberg O, Zangemeister WH, Rosenberg M, Hoyt WF, Stark L. Saccadic eye movement strategies in patients with homonymous hemianopia. Ann Neurol 1981; 9: 537–44.

Miller NM. Walsh and Hoyt's clinical neuro-opthalmology. Baltimore: Williams and Williams; 1982.

Morrison RE, Rayner K. Saccade size in reading depends upon character spaces and not visual angle. Percept Psychophys 1981; 30: 395–6.

Neale MD. Neale analysis of reading ability. Oxford, UK: NFER-Nelson; 1989.

O'Regan JK, Levy-Schoen A, Jacobs AM. The effect of visibility on eye-movement parameters in reading. Percept Psychophys 1983; 34: 457–64.

Pambakian AL, Wooding DS, Patel N, Morland AB, Kennard C, Mannan SK. Scanning the visual world: a study of patients with homonymous hemianopia. J Neurol Neurosurg Psychiatry 2000; 69: 751–9.

Pollatsek A, Bolozky S, Well AD, Rayner K. Asymmetries in the perceptual span for Israeli readers. Brain Lang 1981; 14: 174–80.

Pynte J. Lexical control of within-word eye movements. J Exp Psychol Hum Percept Perform 1996; 22: 958–69.

Randall HG, Brown DJ, Sloan LL. Peripheral visual acuity. Arch Ophthalmol 1966; 75: 500–4.

Rayner K. Eye guidance in reading: fixation locations within words. Perception 1979; 8: 21–30.

Rayner K. Eye movements in reading and information processing: 20 years of research. Psychol Bull 1998; 124: 372–422.

Rayner K, Bertera JH. Reading without a fovea. Science 1979; 206: 468–9.

Rayner K, Johnson RL. Letter-by-letter acquired dyslexia is due to the serial encoding of letters. Psychol Sci 2005; 16: 530–4.

Rayner K, Well AD, Pollatsek A. Asymmetry of the effective visual field in reading. Percept Psychophys 1980; 27: 537–44.

Rayner K, Inhoff AW, Morrison RE, Slowiaczek ML, Bertera JH. Masking of foveal and parafoveal vision during eye fixations in reading. J Exp Psychol Hum Percept Perform 1981; 7: 167–79.

Rayner K, Liversedge SP, White SJ, Vergilino-Perez D. Reading disappearing text: Cognitive control of eye movements. Psychol Sci 2003; 14: 385–8.

Upton N, Hodgson TL, Plant GT, Wise RJS, Leff AP. 'Bottom-up' and 'top-down' effects on reading saccades: a case study. J Neurol Neuropsychiatry Neurosurg 2003; 74: 1423–8.

Vitu F, McConkie GW, Kerr P, O'Regan JK. Fixation location effects on fixation durations during reading: an inverted optimal viewing position effect. Vision Res 2001; 41: 3513–33.

Zangemeister WH, Oechsner U, Freksa C. Short-term adaptation of eye movements in patients with visual hemifield defects indicates high level control of human scanpath. Optom Vis Sci 1995; 72: 467–77.

Zihl J. Eye movement patterns in hemianopic dyslexia. Brain 1995; 118: 891–912.

Zipf GK. The psycho-biology of language. Boston: Houghton Mifflin; 1935.

Appendix
Example of short text passage

A tropical fish has stunned its owner by displaying Lotto numbers on it's side. Mum of three, June Yates, spotted the figures as the pattern of the fish's scales changed at her aquatic store. June decided to keep the fish and is using the numbers in her Lotto selections.