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The eye movements of pure alexic patients during reading and nonreading tasks

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Abstract

We compared the eye-movements of two patients who read letter-by-letter (LBL) following a left occipital lobe lesion with those of normal control subjects and of hemianopic patients in two tasks: a nonreading visual search task and a text reading task. Whereas the LBL readers exhibited similar eye-movement patterns to those of the other two groups on the nonreading task, their eye movements differed significantly during reading, as reflected in the disproportionate increase in the number and duration of fixations per word and in the regressive saccades per word. Importantly, relative to the two control groups, letter-by-letter readers also made more fixations per word as word length increased, especially as word frequency and word imageability decreased. Two critical results emerged from these experiments: First, the alteration in the oculomotor behavior of the LBL readers during reading is similar to that seen in normal readers under difficult reading conditions, as well as in beginning readers and in those with developmental dyslexia, and appears to reflect difficulties in processing the visual stimulus. Second, the interaction of length with frequency and with imageability in determining the eye movement pattern is consistent with an interactive activation model of normal word recognition in which weakened activation of orthographic input can nevertheless engage high-level lexical factors.

Keywords: Pure alexia; Reading; Eye movements; Hemianopia; Word recognition; Fixations

1. Introduction

Letter-by-letter (LBL) reading refers to a neurobehavioral deficit in which premorbidly literate individuals take an abnormally long time to read even single words after they have sustained brain damage. The characteristic feature of this deficit is the 'word length effect', an abnormally large increase in naming latency as a function of the number of letters in the string. Times of 1–3 s per additional letter in a string have been measured for some LBL readers, although there is considerable variability across individual patients in reading speed [34] as well as in strategy [54,57]. When the reading deficit occurs in the absence of other reading, writing or spelling deficits, it is referred to as 'pure alexia' or, as originally defined by Déjerine, 'pure word blindness' (*cécité verbale pure*; [27]). Although almost all LBL readers have a contralateral hemianopia, usually of the right visual field, the field defect is not causally related to the reading impairment; even when words are placed entirely in the intact left visual field (and letters at the end of the word are closest to the fovea), the same monotonic positive relationship between reading speed and word length is obtained [13].

The hallmark word length effect exhibited by LBL readers is generally interpreted as arising from the patients' sequential processing of letters in a string from left to right. Whereas normal readers show small incre-

Abbreviations: ANOVA, analysis of variance; LBL, letter-by-letter; IAM, interactive activation model.

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ments in reading speed as a function of word length for words up to about nine letters in length [39], suggesting that the component letters are processed roughly in parallel (although see [42] for evidence of sequential processing of letters), the positive linear relationship between length and speed (or negative relationship in accuracy [50]) in LBL reading is attributed to the serial processing of each letter (but see [35], for an alternative interpretation). The parallel processing of multiple letters is likely mediated by a region in the left occipital cortex, and recent neuroimaging studies have confirmed the specific activation of a putative 'word form' system in this region (for an overview of these studies, see [30,43]). Consistent with this localization, lesions typically associated with LBL reading are in the dominant occipital lobe and sometimes, but not always, accompanied by damage to callosal fibres in the splenium of the corpus callosum or forceps major [13,22,23,25]. Damage to the occipital orthographic system, then, is thought to induce the reliance on a sequential letter activation strategy and to give rise to the observed word length effect.

Although considerable research has been conducted on the behavior of patients with LBL reading (see [49] for review of recent cases), these studies have been concerned with the patients' single word reading and there are almost no systematic studies of their text reading abilities. One goal of the present investigation is to examine the text reading abilities of such patients. The straightforward prediction is that the behavioral deficit these patients exhibit on text reading is a direct consequence of the word reading deficit. This would suggest that their reading times will simply be affected as sentence length increases (more words per sentence) and as individual word length increases.

A second and perhaps more pressing goal of this investigation is to study the eye movements of patients with LBL reading. To our knowledge, no such study exists and yet, an understanding of the eye movements during reading is potentially very informative. Measures of eye movements have provided a fine-grained and robust record of reading behavior in normal subjects and have significantly informed our understanding of the oculomotor and psycholinguistic variables that influence normal reading [59,65,67]. The purpose of this study, then, is to explore the pattern of eye movements of LBL readers in order to further our understanding of the mechanisms which give rise to this impairment. There are two current and competing accounts of LBL reading, one arguing for a more peripheral locus of deficit and the other favoring a more central locus and they differ with respect to their predictions of the eye movement pattern in the patients. We elaborate each of these perspectives in turn.

1.1. Peripheral accounts of LBL reading and eye movements

The view of LBL reading as arising from a peripheral locus of the reading system would clearly predict a difference in the eye movements of the patients compared with that of normal readers. According to this peripheral view, LBL patients have a perceptual deficit which manifests as a difficulty in activating the orthographic representations of letters [8,9,48,52,57,72]. As a consequence of this deficit, the patients resort to a compensatory LBL strategy as a means of enhancing individual letter activation. Because eye movement control is extremely sensitive to the perceptual conditions of the input, any difficulty in the more peripheral or perceptual aspects of reading would be expected to give rise to alterations in the eye movement of these patients. For example, the account predicts that, in order to increase the orthographic activation of the input, the LBL patients would show an increase in fixations in order that the higher spatial resolution of the fovea might be applied to multiple locations within a word. On this account, just as latency increases with increasing word length, so one should see an increase in the number of fixations as word length increases.

Further evidence to support the idea that a peripheral impairment would manifest in an alteration of the normal eye movement pattern in the patients comes from data obtained with normal readers under difficult reading conditions. Several studies have demonstrated that when reading conditions are difficult and become more taxing perceptually, normal readers resort to a more sequential reading strategy and this serial processing is observed both in their behavioral data and in their eye movement patterns. For example, under natural reading conditions, normal readers make saccades of eight or nine character spaces in length, when print size is in the moderate range [51], and extract useful information from a region extending from the beginning of the currently fixated word to about 15 character spaces to the right of fixation (although for the purpose of identification, information is used from only five to seven character spaces to the right [45,46]). Under challenging conditions, however, for example when text quality is poorer, 'perceptual span' is shortened [59,65], causing subjects to make more fixations especially as word length increases, a strategy thought to enhance stimulus quality [53]. Under these more difficult conditions, the duration of fixations, normally of 200–250 ms, is also lengthened and the number and duration of regressive saccades, which typically constitute 10–15% of the saccades, are also increased [65,67]. Finally, many of the alterations in the oculomotor pattern during reading are found in subjects with developmental dyslexia. These patients have significantly longer fixations, smaller saccades, more fixations per line of text and more regressive saccades both within- and across-words [26,36,55,64].

If LBL reading results from a peripheral impairment in activating orthographic representations from the input, then the pattern of eye movements that we observe for the LBL readers should reveal the same alterations as those evident for normal readers under these more challenging reading conditions. We predict, therefore, that we will see an increase in the number of fixations per word, in the duration of the fixations and in the number of regressive saccades in the LBL patients relative to their control counterparts. Moreover, these alterations should increase disproportionately as a function of word length, to directly reflect the LBL reading.

If we do observe any alteration in the eye movement performance of these patients relative to normal control subjects, it will be important to establish that it does not arise from a more fundamental oculomotor deficit and that it is specific to the reading domain. Previous studies have found that eye movements do not differ between developmental dyslexic and normal readers in a task that does not require reading, such as visual search [36,64] although there is a recent suggestion that the dyslexic patients' eye movements might not be completely normal [12,28], and that the dyslexia and poor saccadic control may both be attributable to a more fundamental attentional deficit. The general claim, however, has been that the altered eye movement pattern during reading is not due to a primary oculomotor deficit per se, but, rather, reflects the onerous processing demands on the system incurred by reading [55,59,64] and we expect to confirm this. To evaluate this, we include a nonreading task (visual search) in which we track the eye movements of the patients and control subjects while they search for a single, prespecified target letter amongst distractor letters. Our expectation is that all subjects will perform equivalently on such a task. Even though this task involves letters, it does not involve reading per se. Moreover, it places minimal demands on visual recognition, as increasing complexity of the visual stimulus is known to influence the visual performance of LBL readers adversely [8,52] and so this task requires only that the known target be identified.

In sum, based on the existing data supporting a peripheral deficit in LBL readers and the evidence from normal readers under conditions which stress perceptual variables, one would expect a difference in the eye movement pattern of the patients relative to control subjects under normal reading conditions. If, indeed, the eye movement pattern of the patients does not differ from the controls, this would have serious implications for the peripheral account and would substantially undermine its ability to explain the LBL impairment.

1.2. Central accounts of LBL reading and eye movements

An alternative account of LBL reading is that the limitation in parallel processing in LBL reading occurs at a higher or more abstract level of processing and results from a visual-verbal disconnection, i.e. that the intact visual areas involved in reading are anatomically and/or functionally disconnected from the more semantic/conceptual areas [33]. On this account, the deficit does not affect the early stages of processing or the uptake of the visual information per se but, rather, the sequential processing operates after an orthographic representation has already been activated. For example, some views of LBL reading argue that the bottleneck in parallel processing occurs in the later stages of the reading system, perhaps affecting access to lexical or phonological information [15,16]. The implications of a central account of LBL reading for the eye movement pattern is less obvious than the peripheral account. While it is theoretically possible for central damage to have ramifications for perceptual processing, it is not obvious that this will be the case. For example, although there are no published accounts of the eye movements of patients with acquired dyslexia that arises from a central locus (for example, surface dyslexia), there is no reason to think that that these patients would show an eye movement pattern that is abnormal. This is particularly the case given that their naming latencies are normal [5]. According to this account, then, the eye movements in LBL would most likely be normal and the LBL patients would show the same eye movement pattern, qualitatively and quantitatively, as normal readers in spite of their behavioral deficit.

Having said this, we do know that more central psycholinguistic variables, such as word concreteness and frequency, affect the behavioral responses of LBL readers [9] as well as the eye movements of normal readers [59]. Specifically, in LBL readers, the hallmark word length effect is magnified for words of low versus high frequency and for words of high versus low imageability. Additionally, more central variables such as the lexical status of the letter string [17,68], the semantic category to which it belongs [24,70,73] as well as the number of orthographic and phonological neighbors [15,48] also appear to influence the behavioral responses of these patients. Previously, we have provided an account which attempts to reconcile the seemingly paradoxical presence of these more central effects within an account that places the locus of the deficit at a peripheral stage of reading. This account argues that LBL reading arises within the context of an interactive account of normal reading [9] and that LBL readers make use of the same cascaded, interactive system as normal readers [3]. The critical difference between the patients and normal readers is that the former are prompted to resort to sequential processing more often (manifest either as multiple eye movements or shifts of covert attention) to compensate for the degradation in visual input following the brain damage. Nonetheless, the weak activation from this input propagates to higher-levels of the system to engage lexical/semantic representations partially, and these representations provide top-down support that facilitates subsequent lower-level processing. In light of the feedback from more central reading processes, it would not be surprising to observe the influence of more central variables on the behavior of LBL readers and, consequently, on their eye movements too. This interactive account might then provide a unified explanation of both the early visual and later lexical and semantic findings in LBL reading and might account for the same findings in the eye movement domain.

In the current work, we examine the eye movement patterns of two LBL readers to establish, initially, whether their eye movements during reading differ from those of their control counterparts. We then explore whether any observed alterations are affected by word length, as directly predicted from a peripheral account of the disorder, and whether higher-order lexical/semantic variables influence the eye movement pattern as well (and perhaps even interact with word length in doing so). Finally, to explore whether the alteration in eye movements in the patients is specific to reading, we measure the eye movements of the subjects in a nonreading visual search task.

2. Methods

2.1. Subjects

Two LBL readers, DM, and PC, consented to participate. Neither patient was dyslexic premorbidly and neither had hemispatial neglect as assessed with the Sunnybrook Neglect battery [14]. Both patients had visual acuity of at least 20/40 (with correction if necessary) and neither had glaucoma, retinopathy, or cataracts. We describe the two patients here and then, for each experiment, we describe the relevant group(s) of control subjects. Subjects' consent was obtained according to the declaration of Helsinki and this study was approved by the Institutional Review Board, Rotman Research Institute of Baycrest Centre, Toronto, Canada.

Patient DM, a 58-year-old, right-handed, English speaking real-estate broker, suffered a seizure in February 1991 and underwent a left occipital lobe resection for a hemiglioblastoma in April 1991, followed by radiation therapy in June 1991. She was first seen by us in December 1992 when she was in remission. At that time, she had noticed a profound difficulty with reading, especially with long words, but reported no other neuropsychological deficits. At testing, DM had a right hemianopia involving the macula as assessed by confrontation and with automated perimetry (Humphreys 30-2 program). An MRI scan in November 1992 reveals a left temporo-occipital lesion including Brodmann areas 17, 18, 19, 21, 22, 23, 27, 29, 30, 31, 37, 39 (note the presence of a shunt, Fig. 1). DM died in 1993.

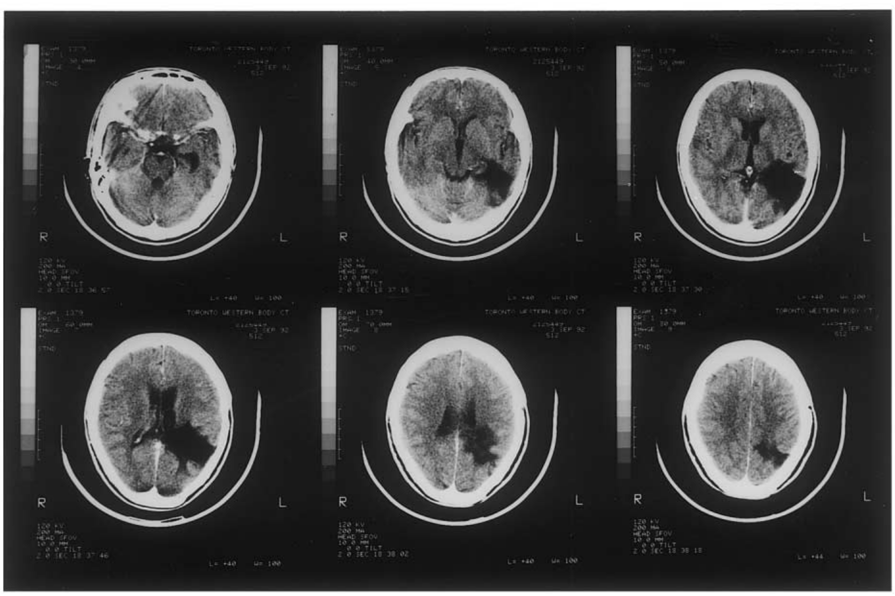

Fig. 1. MRI scan of DM's lesion showing temporo-occipital damage to areas 17, 18, 19, 21, 22, 23, 27, 29, 30, 31, 37, 39 (note the presence of the shunt).

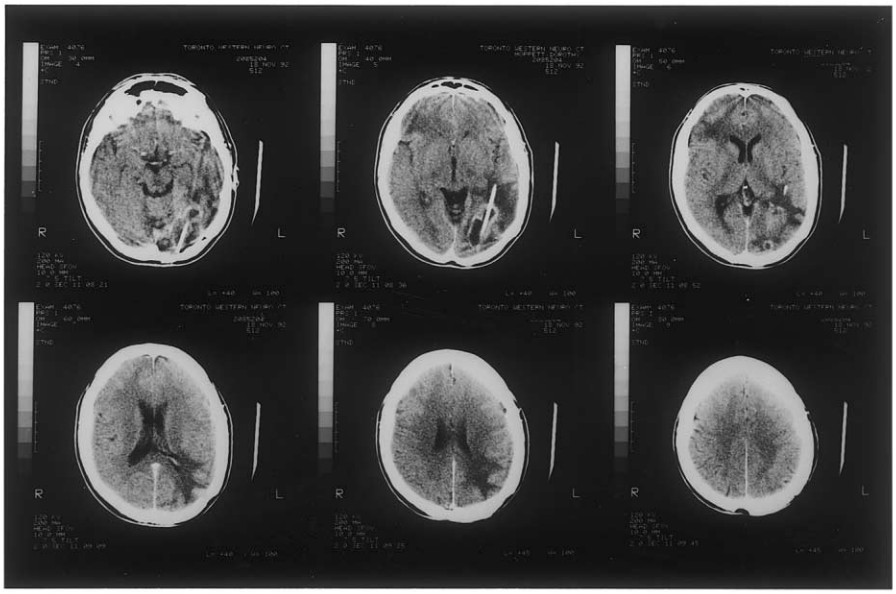

Fig. 2. MRI scan of PC's lesion showing temporo-occipital damage extending to the inferior parietal lobe and implicating Brodman areas 19, 21, 22, 37, 39, 40.

Patient PC, a 40-year-old, right-handed female, who was resident in Canada, was born in Hong Kong and spoke English as her first language. She had an intraventricular meningioma resected during a visit to Hong Kong in mid-1992. A MRI scan from September 1992 showed a temporo-occipital lesion extending to the inferior parietal lobe and implicating Brodmann areas 19, 21, 22, 37, 39, 40 (Fig. 2). Besides slow reading, PC thought she might have suffered some memory problems but reported no other neuropsychological deficits. On automated perimetry (Humphreys 30-2 program), PC had a right hemianopia involving the macula.

2.1.1. Reading behavior of patients

The ability to identify single letters is critical for all subsequent experiments and, to ensure that the LBL patients could do so, a single letter was presented on a computer screen in the third character space to the left of fixation (to circumvent the right-sided hemianopia) for 17 ms (the limits of the computer presentation subject to refresh rate). Both DM and PC named the 52 letters (upper and lower case) well, with scores of 90% and 100% accuracy, respectively[1], suggesting that they can identify single letters well enough to support reading.

To examine their word reading performance, we had the patients name out loud words of three, five and seven letters in length, on one occasion, and perform a lexical decision task on these same words which were mixed with orthographically legal nonwords, on a second occasion. A frequency of 20/million words was used to divide the words into high and low frequency groups [41], with a mean of 13.7 for the low frequency and 279 for the high frequency words. Imageability ratings were taken from the MRC database [21] and words with ratings exceeding 525 were classified as high imageability and those below 525 as low in imageability (range of scale is 0–700). Latency and accuracy were both measured. Because the procedure used here is fairly standard (see [9,10] for further methodological details), only the results are reported here. Two right-handed, native English-speaking female subjects, JD and AS, aged 45 and 46 years, both of whom have participated in a previous study [8], served as control subjects. Neither had any history of neurological deficits and both had university degrees as did DM and PC.

Table 1 presents the accuracy data for the patients and control subjects, as well as the mean reading times as a function of word length and the slope of the latency function, calculated by regressing reading time against word length. This reading time analysis was conducted after responses that exceeded two S.D.s from the mean of the particular cell were excluded and error trials were replaced by the original mean of the cell. An analysis of variance (ANOVA) including group, word length, frequency and imageability was done on the naming latency and lexical decision reading times (words only). For each analysis described here, the naming latency significance values appear before those

[1] Although the accuracy rates are high, this does necessarily mean that there are no visuo-perceptual impairments in these patients. For a discussion of the types of impairments that are possible even with accuracy rates in this range, see [9]. Also, because we do not have reaction time data for this task, we do not know whether performance is indeed normal.

Table 1
Accuracy and reading time slopes for naming latency and lexical decision

	DM	PC	Controls
Naming latency			
Accuracy (%)	98	88	100
Mean reading time			
Three letters	2303	3875	533
Five letters	4540	4429	563
Seven letters	5147	7645	580
Slope	711	942.5	11.75
Lexical decision			
Accuracy (%)	97	93	98
Mean reading time			
Three letters	3219	3766	579
Five letters	4406	5111	605
Seven letters	7240	6202	671
Slope	609	1005.25	21

of the lexical decision task. There were significant main effects of group [naming latency: $F(1, 8) = 1563$, $P < 0.0001$, lexical decision: $F(1, 14) = 58.8$, $P < 0.0001$] with the patients' reading times significantly slower than those of the controls, and of word length [$F(2, 16) = 4.23$, $P < 0.05$; $F(2, 28) = 6.4$, $P < 0.01$] with reading time increasing as word length increased. There was also a significant interaction between group × word length [$F(2, 16) = 3.76$, $P < 0.05$; $F(2, 28 = 5.6$, $P < 0.01$], as is evident by the increased slopes for the patients relative to the control subjects (see Table 1). Reading times were significantly influenced by the joint effect of word frequency and word length [$F(2, 16) = 9.8$, $P < 0.001$; $F(2, 28) = 6.9$, $P < 0.01$] although this was more pronounced for the LBL readers [length × frequency × group; $F(2, 16) = 9.9$, $P < 0.005$; $F(2, 28) = 5.7$, $P < 0.01$]. There was no main effect of frequency or imageability in either task, $F < 1$. Imageability did not interact significantly with group or with length. There was, however, a four-way interaction of imageability × length × frequency × group [$F(2, 16) = 2.5$, $P = 0.05$] in naming latency but not lexical decision. A breakdown of this interaction shows that for the LBL readers, the difference in reading times between high and low imageable words increased as a function of word length but only for the low frequency items. There were no obvious trends involving imageability for the normal subjects and this is probably not surprising given that imageability effects are notoriously weaker than frequency effects in normal subjects [11,75].

These findings confirm the diagnosis of LBL reading for both patients DM and PC. Whereas the control subjects show small but significant effects of word length in naming latency and in lexical decision, consistent with previous reports [31,77], both patients show a dramatic slowing of reading time as a function of string length. PC is the more severely affected given her steeper slopes but both LBL readers fall within the moderate range of severity, compared with other LBL patients [72]. Interestingly, both normal controls and LBL readers are disproportionately affected by frequency as word length increases in both the naming latency and lexical decision tasks although this effect is exaggerated in the LBL readers. This result is consistent with the literature which shows that high frequency words show an advantage over low frequency words across a wide range of tasks including lexical decision [3], word naming [3] and semantic categorization [47]. Effects of imageability on the reading performance of the patients and controls are weaker, manifesting only in naming latency and showing an increase in reading time between high and low imageable words as length increases but only for low frequency words and only in the LBL readers. The weaker effect of imageability in both populations is also consistent with existing literature [9,11,75].

2.2. Eye movements during visual search

The goal of this first eye movement study was to demonstrate that the LBL readers do not have a primary oculomotor impairment that might account for any altered eye movement pattern in reading. To demonstrate this, the subjects completed a visual search task on the same day that they undertook the critical reading task described below.

2.2.1. Control subjects

We recruited two groups of subjects against which to compare the performance of the LBL readers. The first, the Control group, consisted of non-neurolological normal subjects and the second, the Hemianopic group, consisted of patients with brain-damage and hemianopia but not with LBL reading. This latter group is important given that LBL readers typically are hemianopic. These normal and hemianopic subjects have served as control subjects in our previous studies of eye movements [4,7,9]. Note, however, that here we exclude normal subjects 1 and 4 from the original control group reported in [7] as they were not native English speakers, a prerequisite for inclusion here. No subject had cataracts, retinopathy or glaucoma and all consented to participate.

The Control group, made up of seven subjects (three male, four female) with no history of neurological disease, was drawn from the elderly subject pool at the Rotman Research Institute of Baycrest Centre, Toronto. All subjects were right-handed and English-speaking. The mean age of these subjects was 59.2 (S.D. 3.4) and their mean years of education was 13.1 (S.D. 2.9).

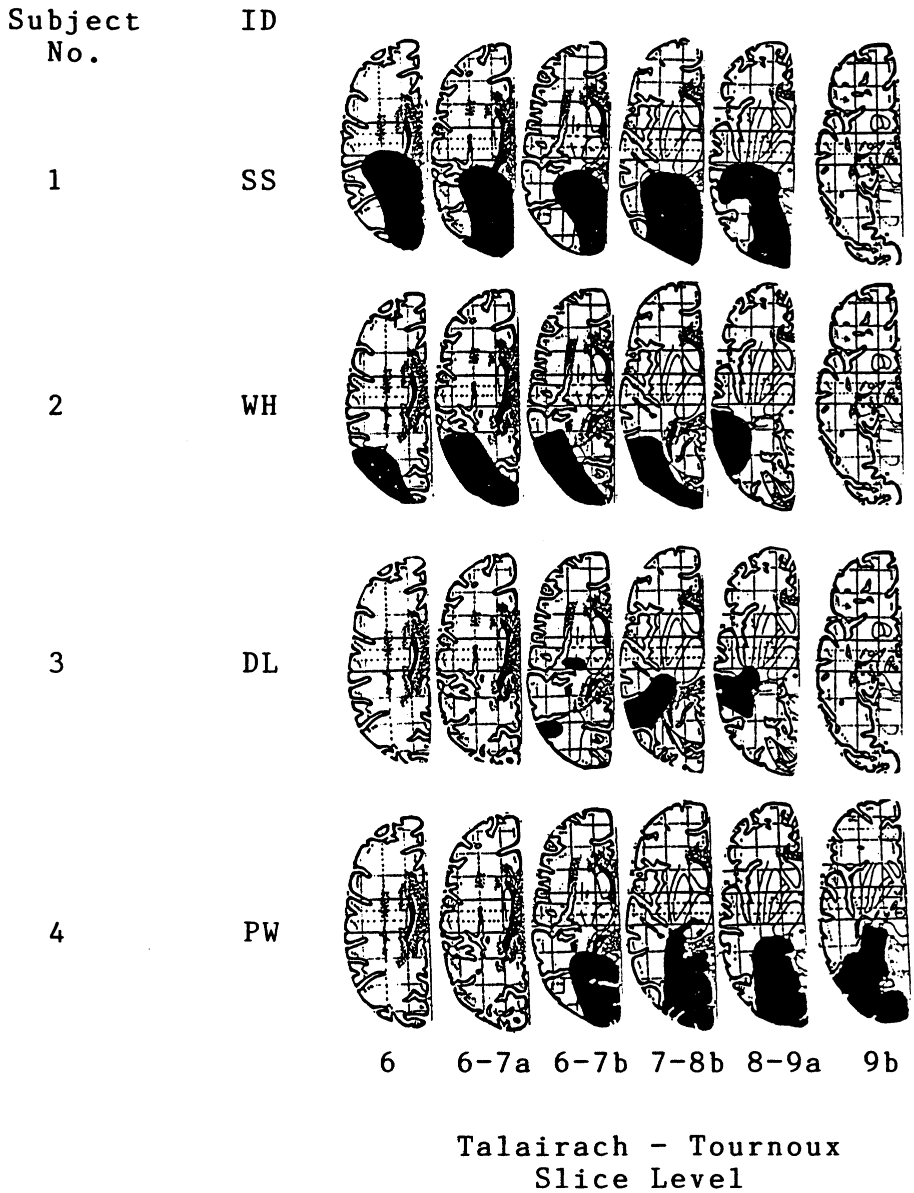

Fig. 3. Templates [76] depicting the cerebral lesions for the four hemianopic patients.

The Hemianopic group consisted of four patients, one female and three male subjects with a mean age of 53.8 (S.D. 17.9) years. All had left homonymous field defects (documented with Humphrey automated threshold perimetry 30-2 program) following right-sided lesions of either the occipital lobe or optic tract. The subjects were medically stable and showed no evidence of LBL reading. The selection of a brain-damaged control group for the LBL readers was difficult — ideally, these patients should have lesions of comparable size to the LBL patients but not be LBL readers. Patients with large left hemisphere lesions either in or outside of occipital cortex do not meet these criteria, however, for the following reasons: if a patient has a large inferior occipital lesion, for example, subsequent to a posterior cerebral artery infarction, they will almost certainly be a LBL reader, and obviously not suitable to serve as a control subject. If a patient has a lesion that affects the superior occipital cortex, the lesion will, in all likelihood, not be as large as that in our patients because there is collateral supply from the middle cerebral artery to the superior occipital regions. Patients who have large lesions affecting regions outside of left occipital cortex are also not obviously suitable as they usually have a language deficit of some form. Our choice, then, was to recruit patients with left hemianopia following right hemisphere posterior lesions. At least two of these subjects have large lesions, comparable in size to those of the LBL patients. Templates depicting the lesion size and location for the four hemianopic patients are shown in Fig. 3 and their neurological and biographical data are reported in Table 2.

Table 2
Biographical details for four hemianopic control subjects

Patient	Sex	Age	Years of education	Time test[a]	Perimetry[b]	OR/OT[c]	Lesion[d]	Volume
1. SS	F	28	13	14	L hemi, Msplit	OR/OT	O, T	103
2. WH	M	55	?	11	L hemi, Msplit	OR	O,T, P,	86.5
3. DL	M	66	13	13	L hemi	OR	P, T, BG	25.8
4. PW	M	66	18	22	L hemi, Msplit	OR/OT	O, Th	111.9

[a] Time of testing post onset in months
[b] Msplit, macular split; L, lower quadrantanopia; hemi, homonymous hemianopia.
[c] Involvement of: optic radiation (OR) or optic tract (OT).
[d] P, parietal; T, temporal; O, occipital; BG, basal ganglia.

2.2.2. Apparatus and procedure

Subjects sat in a chair in a dimly lit room with the head supported by an occipital rest. Eye position was measured using the magnetic search coil technique with 6-foot field coils (CNC Engineering, Seattle, WA). System bandwidth was 0–400 Hz. Subjects wore a scleral contact annulus in one eye while they viewed the target display. The system has a spatial resolution, after analog to digital conversion, of about 1 min of visual angle. At the beginning of the session, the coil was placed in the preferred (right in all our subjects) eye following a drop of topical anaesthetic and remained in place for about 30 min. Subjects viewed with both eyes a tangent screen located 1.14 m away.

The signal from the eyetracker was sampled every 5 ms (i.e. 200 samples/s) by computer. The analytic program identified the start and end of saccades. Fixations were then 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).

Before collecting data, 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 0.25° 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 looked at a black dot (0.25° of visual angle) at each of the four corners of a large board placed on the tangent screen (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. All stimuli were presented on $45° \times 36°$ boards. 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.

2.2.3. Stimuli

A set of letters of the alphabet ($n = 84$) appeared randomly positioned on a board in this visual search task (adapted from Mesulam, 1985). 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. There were 20 instances of the letter ‘A’ pseudo-randomly intermixed with 64 distractor letters. Five ‘A’s were positioned in each of four pre-determined and equally spaced vertical bands, two each to the left and right of the midline. There were 16 distractors per band. This layout was not known to the subjects and was used purely for purposes of analysis. From the subject’s perspective, the search was for a known target in a random array. This organization, however, allowed us to plot the number and duration of fixations as a function of their vertical band (see [7] for results using this method with neglect and hemianopic patients). Subjects were instructed to search the board for all instances of the letter A, to state when they were done, and to report the number of A letters found. There was no time limit.

2.2.4. Results and discussion

DM reported 17 ‘A’s and PC 19 ‘A’s, both within the limits of the normal control subjects’ performance (mean 18.3, S.D. 2.3). Fig. 4a and b show the proportion of fixations and proportion of duration of horizontal eye movements for the three groups separately as a function of vertical band. Although we do not make any strong predictions in terms of the quartile bands, we wanted to confirm in a more precise fashion (rather than across the entire board as a whole) whether the LBL readers differed from the control subjects in any way.

An ANOVA with group as a between-subjects factor, vertical band (1–4 from leftmost to rightmost) as a within-subjects factor and absolute number of fixations

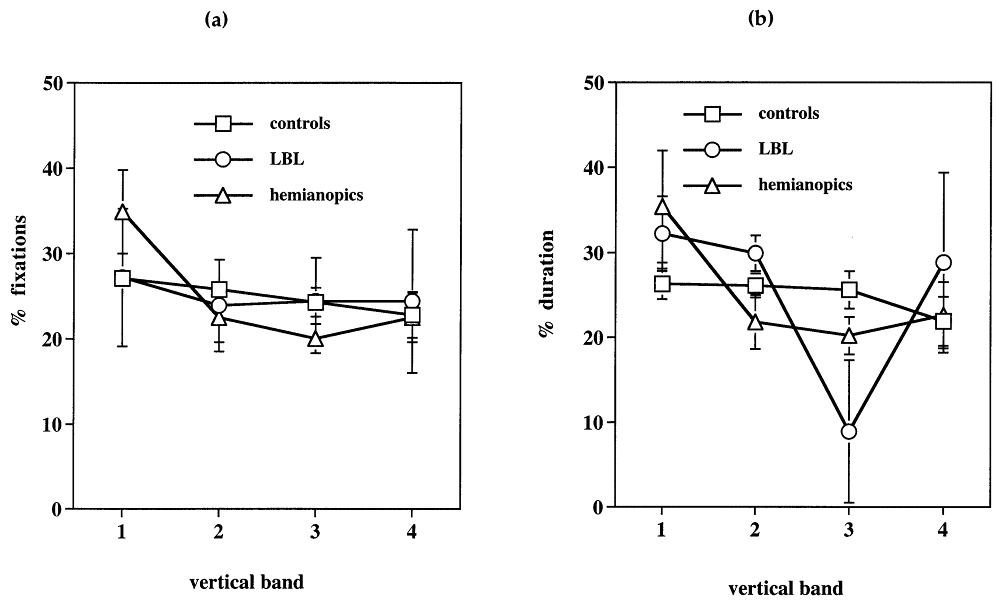

Fig. 4. (a) The percentage of fixations and (b) percentage of duration of horizontal eye movements for the three groups as a function of vertical band in the visual search task.

as the dependent measure revealed no significant main effect of group [$F(2, 10) = 3.2$, $P = 0.08$] although there was a main effect of vertical band [$F(3, 6) = 7.10$, $P < 0.001$] with the largest number of fixations in the first and the final bands (40 and 35, respectively) compared with the middle two bands (30 and 28, respectively). There was, however, an interaction between group and band as the LBL readers showed an even greater increase in fixations than the other two groups for the beginning and end vertical bands [$F(6, 30) = 2.9$, $P > 0.05$]. When we do the same analysis with proportion of fixation as the dependent measure there were no significant main effects of group [$F(2, 10) = 1.5$, $P > 0.1$] nor of vertical band [$F(3, 6) = 2.1$, $P > 0.1$] nor an interaction between them [$F(6, 30) = 0.9$, $P > 0.5$]. The same analysis done yet again but using proportion of duration as the dependent measure similarly showed only a marginal main effect of group [$F(2, 10) = 3.5$, $P = 0.06$]. There was, however, a significant effect of vertical band, $F(3, 6) = 3.8$, $P < 0.05$] with longer search time in the vertical band to the right of the midline (see Fig. 4b), and a marginally significant interaction of group × quadrant [$F(6, 30) = 2.02$, $P = 0.09$]. This interaction comes about largely because one of the two LBL readers spent less than 2% of the time in this quadrant (hence the increased variability and shifted mean in this cell for the LBL readers).

We also compared the mean fixation duration for the two patients (PC 207 ms; DM 221 ms) with that of the other two groups and showed no significant difference between any of them [$F(2, 12) = 2.5$, $P > 0.1$; controls mean 174 ms, S.D. 24.9; hemianopics mean 197 ms, S.D. 19.7]. It should be noted that the mean fixation duration is much shorter here than the 275 ms value standardly reported in the literature [59] although there is always considerable inter-subject variability on this measure. One possible explanation for this difference is that the letters we used were unusually large (subtending 1° of visual angle) although exactly how this might affect the mean fixation duration is not obvious (aside from the possibility that it might speed letter discrimination).

Overall, the results from the visual search task revealed no major differences between the LBL readers and either of the control groups in terms of duration of fixations per band or mean fixation duration. There is a slight difference in that the LBL patients make more fixations than the other groups at the extreme left and right ends of the display but this same pattern is seen in the other two groups albeit not to such an extent. Furthermore, when the proportion of fixations per band is analysed, there is no difference between the groups at the relative left and right ends. Thus, although there are slight differences between the LBL readers and the other subjects on one variable, the overall pattern is the same and performance on the other three variables is not significantly different.

2.3. Eye movements and reading

2.3.1. Subjects

Both the groups of hemianopic and normal control subjects participated in this experiment as well as the two LBL patients.

2.3.2. Apparatus

The apparatus was identical to that used in the visual search task.

2.3.3. Stimuli

Several different paradigms are used to show how eye movements are related to reading (see [59] for overview of the different paradigms). To determine the size of the span of effective vision, for example, the 'moving window' paradigm uses current fixation position to ensure that only a portion of the text surrounding fixation is visible at any one time, by replacing text outside this area by other symbols or letters. This allows one to measure the number of characters processed during a single fixation. Other paradigms allow subjects to view single words, sentences or text freely. We elected to use free viewing of text reading so as to approximate natural reading as much as possible.

We used two separate paragraphs which have been shown to be well suited to adult readers [19]; see Appendix for paragraphs). All subjects read both paragraphs but in counterbalanced order. Each paragraph was presented on a large board, of the same dimensions as the visual search task and, as in that task, each letter subtended 1° of visual angle at a distance of 1.14 m. Although this task was chosen to simulate natural reading, we did ask the subjects to read aloud to obtain both accuracy and latency measures. The verbal responses of the subjects were tape recorded and transcribed off-line. Because the two LBL patients found this reading task extremely difficult, they read only the first six lines of paragraph 1 (three full sentences) and eight lines of paragraph 2 (six full sentences). The control subjects and hemianopic patients completed the entire paragraph in both cases, but only that portion of the data that corresponds to that of the LBL patients was analysed for this study. The two paragraphs varied in several respects, such as the number of words and letters per line, the distribution of frequency of words and so on. Also, one paragraph was left-justified whereas the other right-justified, a manipulation designed for the study of hemispatial neglect [6]. However, in the initial analyses below, this difference in layout did not interact differentially with any of the three subject groups and the variable of paragraph was subsequently excluded from later analyses.

2.3.4. Behavioral results

The transcription of the output of the two LBL readers appears in the Appendix. Their accuracy is good overall, with occasional hesitations but few frank errors (PC read FRUITS as 'fruit' but then corrected herself). The normal subjects made almost no errors in reading. Because, for technical reasons, we had only recorded the responses of one of the hemianopic patients, all of whom read extremely well, we performed the quantitative analysis of reading latency on only the LBL readers and the normal controls. For each of the nine sentences of the text (three from paragraph 1 and six from paragraph 2), we calculated the subject's overall reading time. An ANOVA with group as a between-subject factor, sentence as a within-subject factor and reading time as the dependent measure revealed a significant effect of group [$F(1,7)=48.2$, $P<0.0001$]; control subjects spent an average of 4 s per sentence whereas the LBL readers required 31 s per sentence (the single hemianopic patient took an average of 6.02 s per sentence). There was also a main effect of sentence [$F(8,56)=55.7$, $P<0.0001$] reflecting the differential lengths and complexities of the different sentences. The interaction of group × sentence was significant too [$F(8,56)=33.8$, $P<0.001$] with reading speeds of the LBL readers much more variable than those of the normal subjects across the different sentences. For example, although the control subjects took less time for shorter than longer sentences, with responses of 2.2 for sentence seven (nine words, 45 letters: paragraph 2 starting 'Trees are the best-known …') compared with 8 s for sentence two (29 words, 102 letters: paragraph 1 starting 'When you look at a tree …'), the LBL readers required 15.6 and 61.1 s for these sentences, respectively. The corresponding values for the hemianopic patient for these two sentences are 3.28 and 9.74 s. Although the hemianopic patient's reading is slower than (although not out of the range of) the mean of the controls, the LBL readers take roughly four to five times longer than the hemianopic patient.

The exaggerated reading time for the LBL readers is consistent with the findings from single word reading experiments and perhaps directly predicted from these data. Whereas the normal control subjects have short latencies in text reading, somewhat influenced by sentence length, LBL readers appear to laboriously decode the letters and take a disproportionately long time as sentence length increases. Interestingly, the LBL readers are not grossly inaccurate and this too is consistent with previous data on their single word reading.

2.3.5. Eye movement analysis

Fig. 5 shows the eye movement pattern of the two LBL readers and two representative control subjects for the entire left-justified paragraph. Each fixation is represented as a circle and the size of the circle reflects the duration of that fixation. The difference between the LBL readers and the normal controls is obviously very dramatic. The analyses below quantify these differences and assess them statistically. We first examine these group differences at a global level across the entire text and then look at the effects of more specific variables such as word length, frequency and imageability on eye movements.

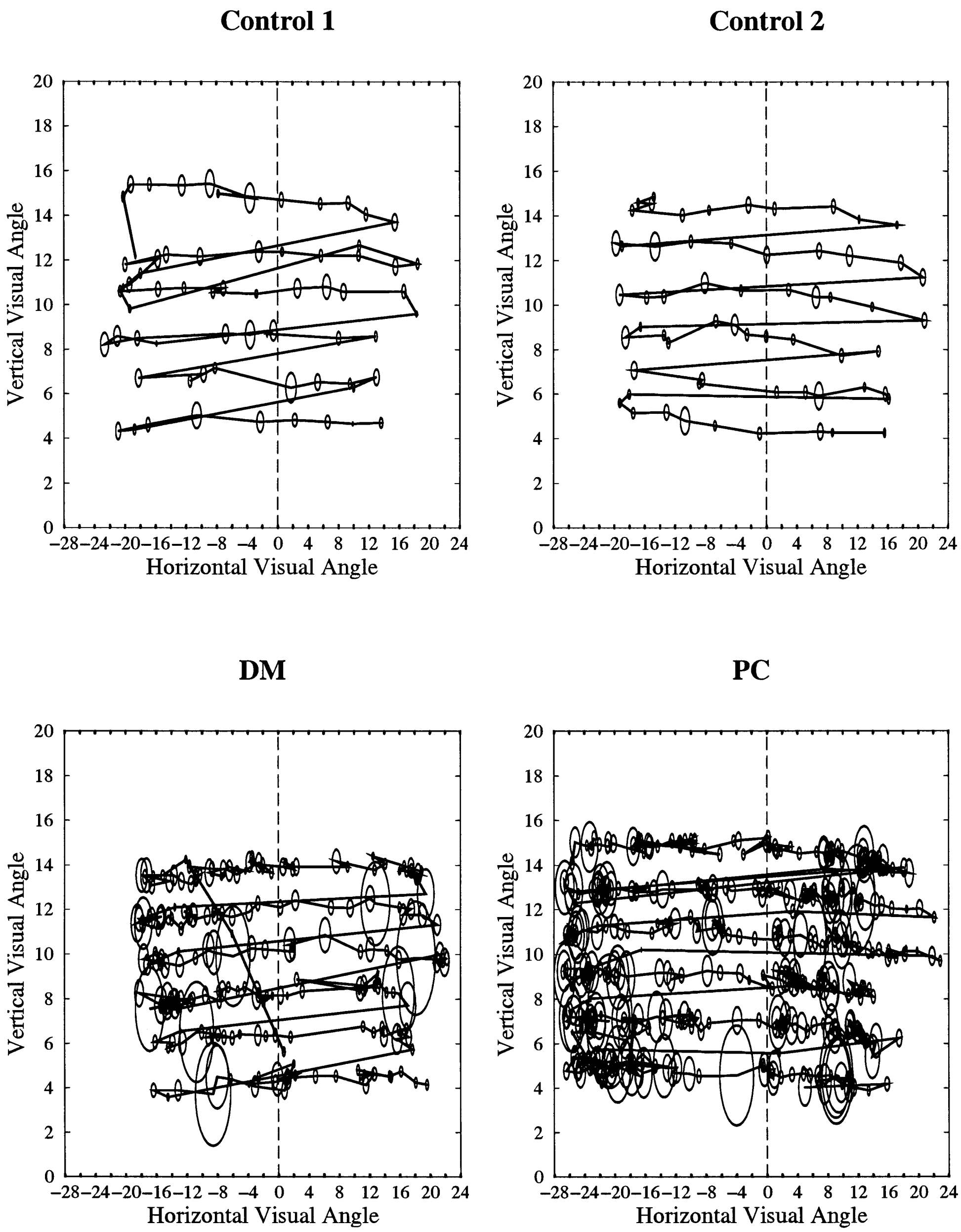

Fig. 5. The number and duration of fixations in x- and y-coordinates for the left justified paragraph for the two LBL readers (bottom two panels) compared with two control subjects (top two panels). The size of each circle depicts the duration of each fixation.

2.3.5.1. Text effects. We conducted different ANOVAs using as dependent measures the number of fixations per word, the mean duration of each fixation, and the number of regressive saccades per word. In all analyses, group was included as a between-subjects measure and paragraph (left or right justified) as a within-subjects measure to determine the influence of paragraph layout. In these and all subsequent analyses, we included only those fixations or regressive saccades that fell on a word as well as any that appeared in the blank space immediately to the left of the word (there were few of these but this is a conservative measure to make sure that we do not exclude any relevant fixations). Fixations that did not obviously fall on text (fell vertically in between lines of words or outside of the screen) were not included although, as has been shown previously [1], these occur only infrequently. Regressions were counted as the number of leftward saccades and this included regressions whose fixations landed on the same word or on preceding words.

The first finding from these analyses is that the paragraph layout did significantly affect performance [number of fixations: $F(1,2) = 7.7$, $P < 0.05$; duration per fixation $F(1,2) = 3.8$, $P = 0.08$; regressions $F(1,2) = 11.9$, $P < 0.01$]; interestingly, however, the left-justified paragraph (the more usual format) was

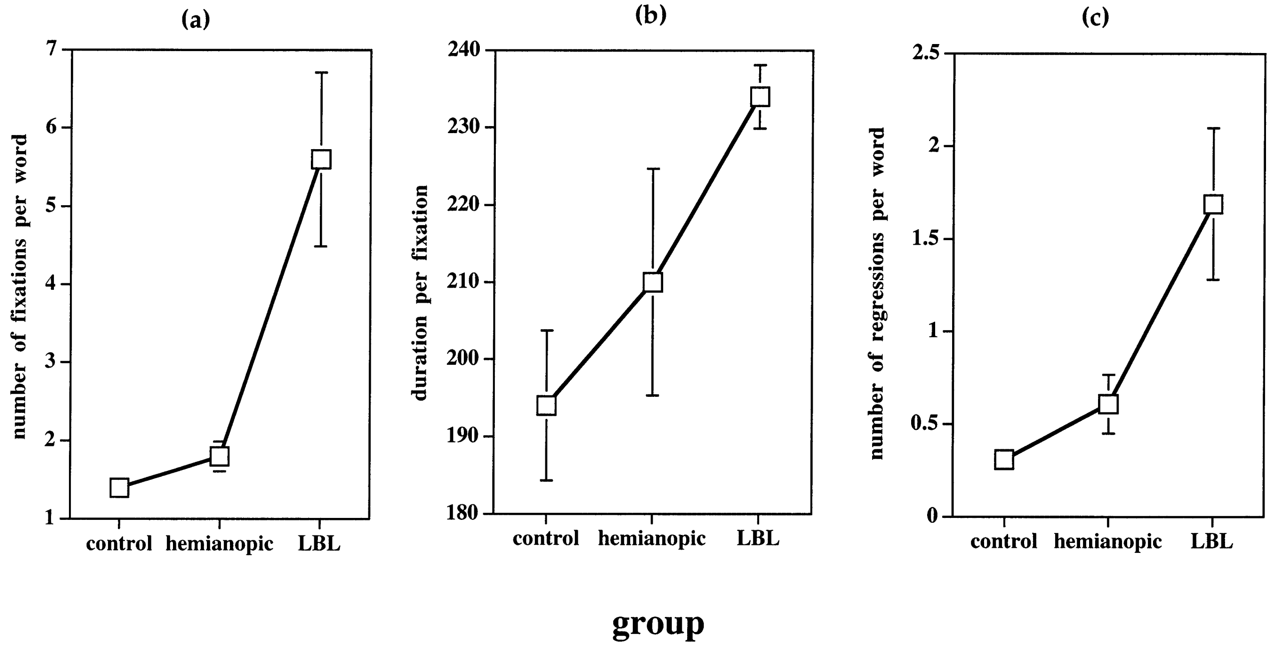

Fig. 6. The mean and S.E. bars for (a) number of fixations per word, (b) duration per fixation per word and (c) number of regressions per word for the control, hemianopic and LBL groups across the entire text.

associated with more fixations and longer duration per fixation than the more unusual, right-justified paragraph. More important, however, paragraph type did not affect the three different groups differentially [number of fixations $F(2, 9) = 3.1$, $P > 0.05$; duration per fixation $F(2, 9) = 0.9$, $P > 0.1$)] except that the LBL readers made slightly more regressive saccades in the left- than right-justified paragraph compared with the other groups [$F(2, 9) = 4.3$, $P < 0.05$]. Overall, then, the unusual layout of the right-justified paragraph does not particularly disadvantage any one group more than any other; hence, we exclude paragraph layout as a variable in the remaining analyses.

As shown in Fig. 6, we see strong group effects across all dependent measures; the LBL patients made significantly more fixations per word [$F(2, 9) = 15.6$, $P < 0.001$] spent more time per fixation [$F(2, 9) = 5.4$, $P < 0.05$] and made more regressive saccades per word [$F(2, 9) = 7.33$, $P < 0.01$] compared to the other two groups, who did not differ from each other. As noted above, the absolute values obtained for the mean fixation durations here are shorter than those typically reported in the literature. Aside from the fact that the size of the letters we used may have caused this, we have no obvious explanation for this discrepancy. It is worth noting, however, that the mean fixation duration values obtained here for reading out loud and for the visual search task reported above are very similar, as is standardly the case in the literature.

2.3.5.2. Word length effects. In the following section, we restrict our further analyses to one dependent measure, the number of fixations per word. The effect of word length on the number of fixations is shown for each of the three groups in Fig. 7. An ANOVA with word length (one to eight letters) and group showed a significant effect of group [$F(2, 9) = 12.5$, $P < 0.005$] with the LBL readers making more fixations per word (mean 5.4) than either the controls (mean 1.3) or hemianopic subjects (mean 1.6) who do not differ from each other

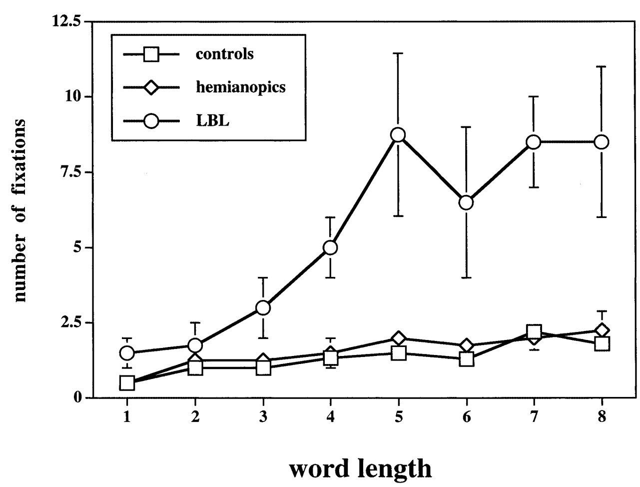

Fig. 7. The mean number of fixations and S.E. bars as a function of word length for each of the three subject groups. Note that with this scale on the y-axis it is not possible to see the error bars for the normal and hemianopic subjects.

$[F(2, 9) = 12.5,\ P < 0.1]$[2]. There was also a main effect of word length, with means of 0.7 and 3.1 fixations for words of one and eight letters in length, respectively, and an increasing trend through the intermediate word lengths $[F(7, 14) = 30.1,\ P < 0.0001]$. Most relevant is the interaction of group × length $[F(14, 63) = 9.4,\ P < 0.0001]$: post hoc analyses of this interaction using Tukey HSD ($P < 0.05$) revealed no significant differences for either the control subjects or hemianopic readers across words of one to eight letters in length, as is evident from Fig. 7. Note that both the control and hemianopic groups show a numeric increase in the number of fixations as word length increases with differences of 1.3 and 1.75 fixations between words of one and eight letters in length for the two groups. This small increase is consistent with the finding that normal readers typically show a slight increment in the number of fixations as words get longer [38,63], especially for words between five and ten letters in length [66]. In contrast, the LBL readers showed a marked effect of length with many more fixations for longer than shorter words (one letter: 1.5; eight letters: 8.5). There was a linear increase in the number of fixations as word length increased from one to five letters (except between one and two letters), followed by an asymptote and increased variability for words with more than five letters. A regression function with length (one to five letters) plotted against number of fixations reveals a slope of 1.78 fixations for each additional letter for the LBL readers in this range.

2.3.5.3. Lexical/semantic effects. Of all the psycholinguistic variables, word frequency perhaps most strongly influences reading performance. Effects of frequency are seen not only on reading time but also on the eye movements of normal readers [37,38,40]; Rayner and Duffy [61], for example, found that the average fixation duration for the first fixation was 262 ms for low and 225 ms for high frequency words (see also [58]).

To determine the effect of frequency on the number of fixations made by LBL readers, we conducted an ANOVA with word frequency and length as within-subject factors and group as a between-subjects factor. The frequency values for the words were obtained from Kuçera and Francis [41]. For this analysis, we used only words with frequencies less than 50 per million as low frequency ($n = 24$; mean frequency is 17.8) and those with frequencies more than 60 per million as high frequency ($n = 92$; mean frequency is 12042.5). Words falling in between the two groups are excluded from the analysis. Because the crossing of the two within-subject factors of frequency and length creates cells with few data points, and because there are no significant reading time effects in the number of fixations across words of five to eight letters in length, we collapsed the word-length variable into short (one to four letters) and long (five to eight letters) words.

As expected, there was a main effect of group $[F(2, 9) = 11.5,\ P < 0.01]$, a main effect of length $[F(1, 2) = 19.3,\ P < 0.01]$ and a two-way interaction of word length by group $[F(2, 9) = 7.5,\ P < 0.02]$. There was also a main effect of word frequency $[F(1, 2) = 59.1,\ P < 0.0001]$, with a mean of 2.0 fixations to high and 2.7 fixations to low frequency words, but this was qualified by an interaction of frequency by group $[F(2, 9) = 14.6,\ P < 0.01]$, reflecting the exaggerated increase in fixations in the LBL readers. There was also a significant interaction between word frequency and length $[F(1, 2) = 6.8,\ P < 0.05]$ but, importantly, and critically for our purposes, this was qualified in the three-way interaction with group $[F(2, 9) = 8.8,\ P < 0.01]$. The major finding, shown in Fig. 8a, is that for LBL readers the increase in fixations for low- over high-frequency words is greater for long than short words whereas there is no significant increase for the other two groups. LBL readers made, on average, 0.5 more fixations on low than high-frequency short words but 3.5 more fixations for low than high frequency long words. The difference between low and high frequency words for normal controls was 0.5 and 0.3 additional fixations for short and long words and the corresponding values for the hemianopic group were 0.25 and 0.75. As is evident, the increase in fixations for low over high frequency words is minimal in these latter two groups.

Imageability effects have also been shown to influence the reading latency in LBL reading, and to interact with word length although not as strongly as in the case of frequency [9]. To examine the interaction of imageability with length on the number of fixations per word, we split the words into high and low imageability categories with the cutoff set at 525 (values obtained from the MRC database [21]). Where no value was available, the word was excluded. Imageability was crossed with length (short/long as above) and with group as the between-subject factor. As with frequency, there was a significant three-way interaction in the data although the magnitude of this interaction is smaller than is the case for frequency $[F(2, 9) = 6.9,\ P < 0.05]$. The results are shown in Fig. 8b. LBL readers made an additional two fixations to low- than to high-imageability short words and 2.5 more fixations to low- than high-imageability long words. The comparable values were -0.3 and -0.7 for the control group and -0.75 and -0.25 for the

[2] Note that because we only include words through eight letters in length as there were too few longer words for this analysis, the mean number of fixations per word is slightly less than is shown in Fig. 8a.

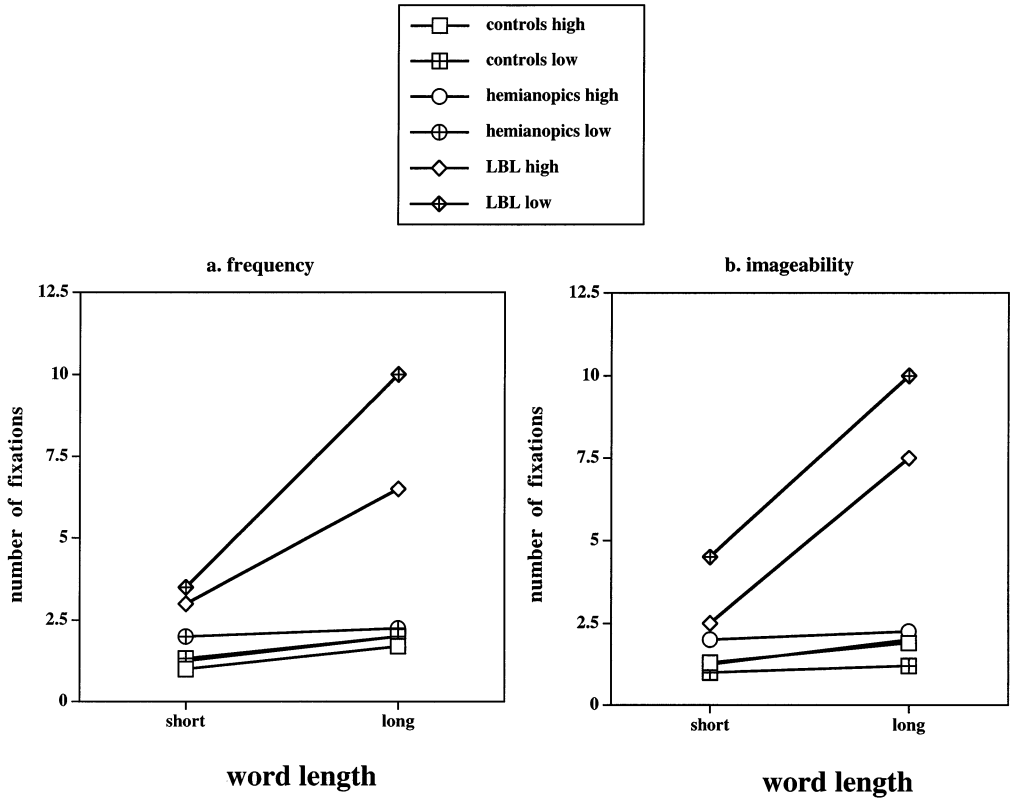

Fig. 8. The mean number of fixations for short and long words for the control, hemianopic and LBL groups as a function of (a) frequency and (b) imageability.

hemianopics, with neither of these two groups showing a significant influence of imageability[3].

3. General discussion

Because of the steep drop-off in spatial resolution as information appears further away from the fovea, eye movements are critical in order to bring new visual information into the high-acuity foveal region for the purpose of identification. Eye movement patterns have been well documented for normal readers and have proved to be highly informative with regard to the oculomotor and linguistic mechanisms mediating reading both under normal and challenging conditions [59]. We studied the eye movements of two patients with pure alexia or LBL reading subsequent to a left occipital lobe lesion to elucidate further the mechanisms underlying this acquired reading deficit. This study had two main goals. The first goal was to examine the text reading performance of the patients as, to our knowledge, this has received minimal, if any, attention in the literature to date. To do so, we obtained behavioral measures of their performance including reading time and accuracy while they read aloud two different paragraphs. The second goal was to determine whether the eye movements of LBL readers differed from those of two groups of control subjects (normal subjects and patients with brain-damage and hemianopia but not LBL reading) and, if so, whether any differences were specific to the domain of reading. To do so, we compared eye movements across a host of dependent measures including number of fixations, proportion of fixations, mean fixation duration, and number of regressive saccades during text reading. We also examined whether the eye movement pattern was influenced by word length as well as by more central psycholinguistic variables such as word frequency and word imageability. To assess whether any differences in the eye movement pattern observed between the patients and control subjects during reading was specific to linguistic tasks or not, we tracked the eye movements of all subjects in a nonlinguistic visual search task in which they searched for a prespecified target letter

[3] We also examined an additional lexical variable, part-of-speech, on the number of fixations across the three groups, and obtained a significant group × part-of-speech interaction, ($F(16, 72) = 5.6$, $P < 0.001$). In this analysis, the normal subjects made more fixations on substantive words (nouns, adjectives, etc) compared with functors (prepositions, articles), consistent with previous results [38]. LBL readers show an exaggeration of this pattern. This finding, however, needs to be interpreted with caution as part-of-speech is confounded with word length and therefore, any contribution of part-of-speech per se is not yet clear.

amongst a random display of letters. To our knowledge, this is the first study that examines the performance of LBL readers while they read text (as opposed to single words) and it is the first investigation of the eye movements of these patients.

The first major finding was that the LBL readers were significantly impaired in their text reading although this manifested primarily in prolonged reading time rather than in accuracy which remained relatively high. Reading time increased as a function of sentence length both in terms of the number of words per sentence and the relative length of the words in each sentence. The impairment in text reading is not unexpected and appears to be directly predictable from the patients' performance on single word reading.

The second critical result was that there were no overall differences between the LBL readers and the two control groups in the nonlinguistic visual search task. This was true both in their behavioral responses and in their eye movements. The number of target letters reported was similar and the proportion of fixations, mean fixation duration and total duration of fixations as well as their spatial distribution did not differ across the three groups. There was a slight increase in the absolute number of patients' fixations at the extreme edges of the display relative to the other two groups but the other groups showed similar tendencies. It is also unlikely that this difference would give rise to the major changes in eye movements observed during reading. Overall, then, these findings attest to the absence of a fundamental oculomotor deficit in LBL readers and are consistent with those studies of children with developmental dyslexia that report no major differences between the eye movement patterns of normal and dyslexic readers [26,36,64].

The final and perhaps most interesting result was that in the eye movement analysis of the reading task, the LBL readers differed significantly from their control counterparts in many ways; the patients made more fixations and fixations of longer duration per word as well as more regressive saccades per word. Furthermore, the number of fixations increased disproportionately as word length increased, and this word length effect became even more pronounced as word frequency and imageability decreased. As is also evident from the findings, the pattern of behavioral data (using reading time as the dependent measure) and of eye movement data (using number of fixations as the dependent measure) are remarkably similar, suggesting that the eye movement pattern reflects the fundamental behavioral impairment rather well.

Before interpreting these findings in a broader theoretical framework, there are some aspects of the empirical data that were unexpected and that require further elaboration. For example, it is puzzling that for the LBL readers the linear increase in fixation with increasing word length (1.78 additional fixation per letter between one and five letters; 1.115 additional fixations per letter across all word lengths) is only evident for words between one and five letters in length especially since the increase in fixations between words of five and ten letters in length is often seen in normal subjects [59]. One trivial explanation for the asymptote may simply have to do with the reduced statistical power with longer words. There are roughly half the number of long compared to short words in the corpus (87 words of four letters or less and 43 words of five letters or more) and, moreover, there are only five seven-letter words and five eight-letter words in the corpus. The reduced power is manifest in the increased variance for the longer words (see Fig. 7) and this likely makes it difficult to obtain clean estimates of fixation number across the entire range of word lengths. The absence of a linear increase in eye movements in the range of the longer words, then, might simply arise from various artifacts of the sample.

A second aspect of the findings that requires elaboration is how these results compare with previous findings. As mentioned previously, there are no other studies to our knowledge which track the eye movements of LBL readers. There is, however, one related study that controls the fixation of a LBL reader and measures reading accuracy under these conditions. In this study, Montant et al. [50] had a LBL patient, CP, report all the letters of briefly exposed words when the fixation location was manipulated. This method provided no opportunity for a second fixation and, when fixation was controlled in this way, CP was not able to report accurately all the letters in a word. He also exhibited a clear viewing position curve indicating better performance when he fixated the second part of a word. Whereas, in our study, we placed no constraints on the reader and therefore intended to elicit natural reading performance and natural eye movement patterns, Montant et al. were more interested in the amount of information extracted in a single fixation. Despite the differences in methods and goals, similar conclusions are reached; in order for a LBL subject to be accurate in reading, especially as word length increases, more than a single fixation is required per word. The same requirement is not true for normal subjects at least within the range of word lengths we tested.

How then do we interpret this set of data and what light does it shed on mechanisms underlying LBL reading? In the introduction, we laid out two accounts of the impairment in LBL reading and their predictions vis-à-vis the eye movement pattern of these patients. A view which argues that the impairment is related to peripheral processes of reading would naturally predict a deficit in the eye movements of the patients during reading. This claim is based both on previous evidence from LBL reading and also on data from normal reading under difficult perceptual conditions. Indeed, we suggested that a normal pattern of eye movements in the LBL readers would significantly challenge a peripheral account of the impairment. The alternative account which argues for a more central locus of the LBL deficit does not obviously predict a change in the eye movement pattern of the patients as the deficit is thought to arise at later stages, once an orthographic representation has been adequately activated.

The finding that the eye movement pattern is significantly different from that of the control subjects along a host of measures appears to support the peripheral account [2,9,73]. Because LBL reading reflects the abnormally weak activation of orthographic input, there is a need to improve the quality of the input. This gives rise to sequential processing of each letter and this seriality is manifest in the increased number of fixations and durations per letter. There is also the potential for an increase in errors of letter identification [6,7] and this might precipitate the increase in regressive saccades. We see similar specific changes in eye movements in normal readers when text quality is poor. Under these conditions, normal readers resort to a more sequential strategy and their eye movements reflect this shift in an increase in the number and duration of fixations and in regressive saccades. Novice readers and developmental dyslexic patients also show these characteristic eye movements, again reflecting the normal system accommodating to the difficult reading conditions it faces.

The same alteration in eye movements as seen in the patients is also observed with experimental manipulations which experimentally ‘convert’ normal readers into LBL patients. Rayner and colleagues [60,62] used a window paradigm in which letters were exposed foveally to normal subjects while all other information was masked. The number of exposed letters varied from one to 33 or, in a control condition, no mask was used. The subjects reported that when the window was small, they resorted to spelling out the words. Although their accuracy was reasonably high (90%), as is true of LBL readers, relative to the unmasked condition, they showed an increase in the number of both forward and backward fixations, and in the average duration of a fixation. These findings are interesting and dovetail well with the idea that LBL readers exhibit the same pattern as normal readers do under more taxing conditions and make more and longer fixations to enhance the quality of the input.

Thus far, the eye movement data are consistent with the peripheral account of pure alexia. We now turn to the effects of frequency and imageability. As is true in the behavioral data, performance is poorer for low than high frequency and imageability words and, to a greater or lesser extent, this is jointly influenced by word length. While on the surface, the presence of these more central psycholinguistic variables seem to be compatible with a central account of the LBL deficit, we outline how they emerge naturally from the interactivity and cascaded processing of the normal reading system. Here, as in our previous work, we appeal to a model of normal word recognition to explain how the system operates [1,2,4]. The interactive activation model (IAM) of normal word recognition assumes that orthographic input is coded and its activation propagated through the rest of the system, activating corresponding lexical and semantic representations [44,69]. Importantly, in this system, processing is cascaded and interactive so that activation from individual letters propagates immediately and continuously through the system, rather than awaiting completion of processing at the lower-level. Activation at higher levels feeds back to support lower-level processing that is consistent with it. Thus, cascaded, interactive processing causes early letter activation to feed forward and partially engage word representations, which in turn feed back to the letter level to influence subsequent processing. Under normal circumstances, the activation of higher-order lexical and semantic representations produces the frequency and imageability effects; for example, the system is able to more rapidly activate representations of words that are higher in frequency (lower resting threshold) than those that are lower and then to settle on a single output.

The powerful interaction of length with frequency and imageability in LBL results from the same system in the following way. Orthographic input (and other visual input) is weakly activated following the occipital lesion [8,20,29,32,71] and, in the model, this is conceived of as damage to either the letter feature level (the strokes making up the letter) or between this level and the letter level (containing the representation of the entire letter). Because of this damage, only weak or partial activation of the letters in a word is possible and this is insufficient for explicit identification of the word. As no word unit is sufficiently activated to exceed the response threshold, the system must resort to sequential processing of individual letters to enhance their perception, hence the word length effect and the increase in fixations and their duration. Although the initial, letter activation may be weak, it nonetheless activates the correct word more than its competitors, and produces more activation than that produced by a nonword (see [44]). This lexical activation which is propagated into the system adds to the cumulative activation at the higher lexical and semantic levels and also feeds back to the letter level to facilitate subsequent recognition of the word’s letters. Now, because longer words take longer to process sequentially, they allow more opportunity for top-down lexical factors to influence reading times as well as eye movements [9,18,56]. Thus, frequency and imageability will influence recognition more for seven-letter than three-letter words, resulting in an interaction of these lexical variables with length. Thus, even with weakened input to this normal system, it is still possible to observe the influence of higher order lexical and semantic variables on performance and the interactions of these with length are observed both in naming latency as well as in eye movement. A very similar explanation for the effects of frequency and imageability on visual word reading errors in a single patient, AT, is provided by Sinn and Blanken [74]. According to this account, the deficit in LBL readers is to peripheral or early processes but it does not preclude the influence of higher-order variables on the behavioral or eye movement performance.

How this interactive system might operate with regard to eye movements is illustrated in computational simulations using an artificial neural network which is based on some of the same fundamental principles as the IAM. In this model, Plaut [56] analysed the sequential phonological output generated in response to written input. Importantly, he allowed the network to refixate the input when there was difficulty activating the orthographic representations. To simulate LBL reading, input letter activations were corrupted by noise so that the damaged model's reading accuracy fell from 99.3% to 90%, a small drop consistent with the relatively preserved reading accuracy of LBL readers. Of most relevance, however, is the increase in the number of fixations in the damaged model compared with the intact model. Whereas the intact model made an average of 1.32 fixations/word, the damaged model made 2.20 fixations, significantly more. The increase in fixations under damage was also strongly influenced by word length; while the intact model showed a small increase in the number of fixations between four- and six-letter words, with a slope of 0.18 fixations/letter, the damaged model had a slope of 0.49 fixations/letter over the same word-length range. There were also frequency effects; the impaired model made fewer fixations on high- than low-frequency words and this difference was greater for six- than for four-letter words. Although the Plaut model read single words and our patients read text, the findings are remarkably similar. Taken together, the behavioral studies and the simulations both reveal how an increase in fixations and duration, which arises because of degraded input, is influenced jointly by word length and by other psycholinguistic variables. The simultaneous and interactive influence of word length and these more central variables is manifest in the behavioral responses of the patients in single word and text reading and the same effects are observed in their eye movements. We suggest that this profile of performance and the influence of these different variables can all be accounted for in a model of normal reading in which input activations, degraded or not, are propagated through the system and engage higher-order representations which, in turn, impact the processing of the bottom-up information.

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Appendix A. Text for each of the two paragraphs and PC and DM's reading responses

Text in square brackets has been analysed for this paper.

A.1. Paragraph 1

[Not only the leaves but also the flowers, fruit, seeds, bark, buds, and wood are worth studying. When you look at a tree, see it as a whole; see all its many parts; see it as a living being in a community of plants and animals. The oldest trees live for as long as three or four thousand years.] Some grow almost as tall as a forty thousand sky-scraper. The largest trees contain enough wood to build dozens of average size houses. Trees will always be one of the most important natural resources of our country. Their timber, other wood products, turpentine and resins are of great value. They are also valuable because they hold the soil, preventing floods. In addition, the beauty of trees, the majesty of forests and the quiet of woodlands are everyone's to enjoy. Trees can be studied at every season, and they should.

A.2. Paragraph 2

[Trees brighten the countryside and soften the harsh lines of city streets. Among them are our oldest and largest living things. Trees are the best-known plants in man's experience. They are graceful and a joy to see. So it is no wonder that people want to know how to identify them. A tree is a woody plant with a single stem growing to a height of ten feet or more.] Shrubs are also woody, but they are usually smaller than trees and tend to have many stems growing in a clump. Trees are easiest to recognize by their leaves. By studying the leaves of trees it is possible to learn to identify them at a distance. One group of trees has simple leaves while the others have compound leaves in which the blade is divided into a number of leaflets. The leaf blade may have a smooth uncut edge or it may be toothed.

A.3. PC's verbal output in paragraph reading

A.3.1. Paragraph 1

Not only the leaves but also the flowers, fruits [fruit], seeds, bark, buds, and wood are worth studying. When you look at a tree, see it as a whole; see all its many parts; see it as a living being in a community of plants and animals. The oldest trees live for as long as three or four thousand years.

A.3.2. Paragraph 2

Trees brighten [brighten the] the country [country-side] and soft [and soften] the [the] harsh [the harsh aa] lines of city streets. Among [among] them are our oldest and largest living things. Trees are the best-known plants in man's experience. They are graceful and a joy to see. So it is no wonder that people want to know how the identity [aaaaa] them. A tree is a woody plant with a single stop [aaa single stem] growing to a height of ten feet or more.

A.4. DM's verbal output in paragraph reading

A.4.1. Paragraph 1

Not only the leaves but also the flowers, fruit, seeds, bark, buds, and wood are worth studying. When you look at a tree, see it as a whole; see all its many parts, see it as a living being in a com[I think it is] community of plants and animals. The oldest trees live [the oldest tree live … does not make sense] for as [something is not quite making sense as] long as three or four thousand years.

A.4.2. Paragraph 2

T-amm-trees brighten the country side and soften the harsh lines of city streets. Among [among] them are our older and larger living things. Trees are the best-known plants in man's experience. They are graceful and a joy to see. So it is no wonder they [no] that people want to know how to identify them. A tree is a woody plant with a single stem [ummm] gro-growing to a height of 10 feet or more.

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