Brain (1995), **118**, 891–912

Eye movement patterns in hemianopic dyslexia

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Summary

Homonymous parafoveal field loss impairs reading at the visual-sensory level. To elucidate the role of parafoveal visual field in reading, reading eye movements were recorded, by means of an infra-red registration technique, in 50 patients with homonymous hemianopia and visual field sparing ranging from 1° to 5°; for comparison, a group of 25 normal subjects was studied. The degree of reading impairment in patients was found to depend on the extent of visual field sparing. Patients with right-sided loss of parafoveal visual field were more impaired than patients with left-sided loss. Eye movement reading patterns paralleled this observation. Left-sided field loss mainly impairs return eye movements to the beginning of a line, while right-sided field loss is characteristically associated with prolonged fixations times, reduced amplitudes of saccades to the right, and many regressive saccades. The analysis of the durations of fixations, and the amplitudes of saccadic eye shifts to the right, and their mutual dependencies, suggests that the perceptual window ('reading span') is altered: its spatial size is reduced, while its temporal extent is increased. The analysis of reading eye movements in 20 patients, who were treated for their hemianopic reading disorder, revealed, in part, a normalization of the eye movement pattern after treatment, indicating that the lost parafoveal field region can be successfully substituted by oculomotor adaptation. Our observations underline the importance of the parafoveal visual field for reading and support the hypothesis of a serial interplay between sensory-perceptual and cognitive factors in reading. Furthermore, reading eye movements appear to be guided primarily by parafoveal information processing; however, eye movement patterns show relative plasticity with respect to 'local' adaptation when the parafoveal field region is lost. This adaptation can best be explained by a change of the perceptual window which appears to be guided mainly by top-down influences. As to the brain lesion which may be responsible for the lack of effective oculomotor compensation, damage to the occipital white matter appears the most crucial condition because it may disconnect visual cortical areas, and interrupt subcortical-cortical connections which are part of a neural network subserving directed visual attention and associated saccadic eye shifts.

Keywords: hemianopia; reading; eye movements; practice

Introduction

The reading process consists of several components, ranging from visual processing at an early stage, to semantic and phonological processing at later stages (for comprehensive reviews, *see* Shallice, 1988; Hillis and Caramazza, 1992). While varieties of acquired dyslexia have attracted most attention in the neuropsychological literature, only few reports deal with reading impairments caused by visual deficits. However, difficulties at the level of visual processing can interfere with reading because disrupted or missing text information impairs access to the representation of words in the grapheme or orthographic input buffers. Visual field disorders, impaired foveal functions (including visual acuity and spatial contrast sensitivity), visual neglect and visual agnosia have been reported to impair reading at various stages of visual processing (Shallice and Warrington, 1977; Levine and Calvanio, 1978; Zihl, 1989; Behrmann *et al.*, 1990). Parafoveal visual field loss represents the most common cause of impaired reading (Zihl, 1989), underscoring the crucial importance of visual processing, in addition to lexical, semantic, phonological and motor processing components. It was Wilbrand who in 1907 coined the term 'hemianopic dyslexia', and suggested that parafoveal field loss is the main cause for this type of reading disorder. Using electro-oculography, Mackensen (1962) and Gassel and Williams (1963) found that hemianopic dyslexia was associated with a fragmentation and irregularity of eye movements, which were more pronounced in cases with right-sided field loss.

Despite a heavy debate concerning the contribution of visual and oculomotor functions in reading, it is commonly agreed that parafoveal visual field plays a crucial role for both text recognition and guidance of eye movements in reading. The fovea shows the highest acuity and, thus, possesses the resolving power required for discrimination and identification of letters. Since visual acuity decreases sharply with increasing eccentricity (Anstis, 1974), the parafoveal visual field only allows gross feature information processing, i.e. the perception of the shape and length of words. Both the foveal and the parafoveal visual field regions act as a common 'perceptual window' and provide the basis for the so-called perceptual span (also word recognition or reading span), which is defined as the field of useful vision during an eye fixation (McConkie and Rayner, 1975). Its extent depends upon the physical properties of the characters and on text variables (e.g. difficulty) but is, in general, in the range of 8° (Ikeda and Saida, 1978; Rayner and Bertera, 1979). The perceptual span exceeds the average-sized word at fixation (Rayner and Pollatsek, 1987) and is larger than the mean size of saccades in reading (Ikeda and Saida, 1978), suggesting that word information can in fact also be extracted, at least partially, from visual field locations outside the fovea. Readers of left-to-right orthographies acquire more information from the right side of fixation than from the left, indicating that the perceptual span is asymmetric; it extends far more to the right (up to 15 characters) than to the left (three to four letters) (McConkie and Rayner, 1975, 1976; Rayner and Bertera, 1979).

The perceptual span is not only defined by its spatial, but also by its temporal extent, which corresponds to fixation time or gaze duration, and is defined as the total period of fixation on a word, or extract of a text, before another word or part of the text is fixed upon (Rayner and Pollatsek, 1987). In skilled readers, length of perceptual span was found to be in the range of 200–250 ms (Yarbus, 1967; Rayner, 1978). Information across fixations is integrated, i.e. foveal and parafoveal text information is used by the reader to maintain continuous text information acquisition and to reduce recognition time (Rayner *et al.*, 1978). Difficulties in recognizing characters and words, and in understanding the meaning of the text, become manifest in the reading eye movement pattern; the duration of fixation is increased and the number of regressive saccades, which normally represent about 10–20% of reading time, is progressive (Yarbus, 1967; Rayner, 1978). Thus both duration of fixation and percentage of regressive eye movements are thought to represent cognitive processes in reading.

The role of the central visual field in the processing of text information can be studied more directly in patients with parafoveal visual field loss due to postgeniculate brain damage. The recording of eye movement patterns in such patients can provide important insights into the perceptual and cognitive processes occurring in the 'pathological' condition of visual field loss, and may also contribute to the understanding of how the various stages of visual processing involved in reading are organized and interact with each other. Furthermore, the analysis of eye movement patterns in patients with hemianopic field loss before and after treatment allows the study of the role of oculomotor adaptation in substituting for the parafoveal visual field loss in these patients.

Subjects for 'before treatment' investigation

Fifty patients (22 females, 28 males, all right-handed) participated in this study. They had suffered stroke in the territory of the posterior or medial cerebral arteries. Brain damage was verified by cranial CT or MRI. Half of the patients showed left-sided (LH-group), the other half right-sided (RH-group) hemianopia. Patients were selected from a larger group of hemianopic subjects (n = 108) and were matched, as far as possible, for age, time since lesion and visual field sparing. The mean age of LH-patients was 43 years (range 21–64), while that of RH-patients was 38 years (range 18–56). The time elapsed between the occurrence of brain damage and the first recording of eye movements varied between 3 and 12 weeks in the LH-group (mean 5.8 weeks), and between 4 and 9 weeks in the RH-group (mean 5.9 weeks). Patients with associated cerebral visual disorders, especially concerning contrast sensitivity (Hess *et al.* 1990) and visual adaptation (Zihl and Kerkhoff, 1990), or with disturbances of the anterior visual pathways or of the oculomotor system (as revealed by detailed ophthalmological examination), and patients suffering from additional neuropsychological deficits, including aphasia or alexia, were not included. (For testing of visual neglect, *see* below.) All patients had a comparable level of education (at least 5 years). Monocular visual acuity was at least 0.90 for near and far vision. Since optical aids, other than contact lenses, would prevent recording of eye movements, subjects with spectacles were also excluded. Furthermore, patients with cataracts (especially older subjects) were not accepted for this study.

Eye movements were recorded when patients were referred to our clinic for visual field examination; these results are presented in the first section. Furthermore, to study in more detail oculomotor adaptation processes, eye movements were recorded in a group of 20 patients before and after treatment; these data are presented in the second section. Eye movements were also recorded, for comparison, in a control group of 25 healthy right-handed subjects (12 females, 13 males; mean age 38 years; range 19–57 years). All patients and control subjects gave informed consent to participate in this study

Methods

Visual field testing

Monocular and binocular visual fields were determined quantitatively using a Tübingen perimeter (Zihl, 1989). Eye position was monitored through a telescope. The diameter of the target was 27 min of arc of visual angle, its luminance was 102 cd/m^2. Background luminance was 3.2 cd/m^2. The target was moved with a speed of ~2°/s from the periphery towards the centre of the perimeter. The patients were instructed to fix on a small red spot of light (diameter 30 min of arc) in the centre of the sphere and to respond to the appearance of the target as soon as the light target was detected. The extent of the visual fields was determined along 16 meridians. Perimetric resolution in this testing condition was 30 min of arc. Since one main interest was the assessment of the influence of parafoveal field loss on reading, the degree of sparing was a further selection criterion for this study. In both the LH- and the RH-groups, the same number of patients had the same degree of field sparing, i.e. five patients had always either 1°, 2°, 3°, 4° or 5° of sparing.

Assessment of visual neglect

In addition to detailed perimetric testing, various tests sensitive for demonstrating unilateral visual neglect were also administered to the patients. The tests were similar to those described in the Behavioural Inattention Test (Halligan *et al.*, 1991) and included visual search, letter and star cancellation, figure and shape copying, line (length 30 cm) bisection, and drawing from memory. None of our patients fulfilled the criteria proposed by Halligan *et al.* (1991) for the diagnosis of unilateral visual neglect. In particular, none of our patients omitted targets in the hemifield contralateral to the damaged hemisphere during the search and cancellation tasks; copying and drawing from memory were entirely normal. In the line bisection task, 17 out of 25 patients with a left-sided hemianopia shifted the midline to the left (mean 2.2°; SD = 0.82; range 0.9–3.6°), and 15 out of 25 patients with a right-sided hemianopia shifted the midline to the right (2.5°; SD = 0.87; range 0.8–4.1°). This observation is consistent with earlier reports showing that hemianopic patients, as opposed to patients with unilateral visual neglect, show a tendency to shift the midline towards the affected side (Zihl and von Cramon, 1986).

Reading

For the assessment of reading performance, horizontal and vertical number and word reading, and horizontal text reading was tested. In the reading-of-number tests, 11 LH-patients omitted the first number(s) of items consisting of five to seven digits (mean omissions 1.5; range 1–3). The RH-patients, as a rule, hesitated to read the whole number, and it took them a longer time to complete the task. Only four cases omitted one digit at the end of the number, but five cases omitted one or even two digits within the number. When instructed to look carefully to the left or right, all patients read the numbers correctly. A similar picture emerged for reading single words of varying lengths (two to 11 characters). In reading vertically arranged numbers or words of the same length, all LH- and RH-patients read them correctly.

The most striking difficulties were found in text reading. The text consisted of 180 words arranged in 20 lines. Normal subjects (n = 25) required, on average, 1.50 min (SD = 0.34; range 0.7–2.2) to read the text aloud; seven subjects made one reading error which was not corrected. The LH-group required a mean reading time of 3.28 min (SD = 0.83; range 2.1–5.7) and made, on average, 3.5 errors (range 0–7), whereas five patients read without error. The errors consisted mainly of omissions of small words or prefixes, especially at the beginning of lines; only seven errors (10% of total errors) were not due to omissions. The RH-group required a considerably longer reading time (mean 6.33 min; SD = 2.21; range 2.2–11.4) and made, on average, many more errors (mean 12.7; range 2–16). These errors resulted mainly (84%) from omissions of small words and of suffixes, and also of syllables within longer words. The impairment in reading, as defined by the number of errors and by reading time, was related to the degree of field sparing. The LH-patients with 1–2° of field sparing (n = 10) made 84% of total errors, while patients with 3° made 16%. In the RH-group, patients with 1–2° of sparing made 67% of total errors, while patients with 3° made 19% and patients with 4–5° of sparing made 14%.

In summary, omissions in our patients were restricted to reading longer words and numbers; their difficulties were clearly related to the side of the parafoveal field loss and depended on its severity: the smaller the degree of field sparing, the more pronounced was the impairment. All patients were aware of their reading difficulties and did not show signs of anosognosia when confronted with their visual disability.

Eye movement recording

Eye movements were recorded using the pupil-corneal-reflection method (Young and Sheena, 1975). The equipment consists of a microprocessor system (Debic 84, Demel, Haan, Germany) connected to a video system. This eye movement recording system allows a spatial resolution of 0.15°, and a temporal resolution of 20 ms. The subject's dominant eye is illuminated by invisible infrared light and the reflections are recorded by video camera. The respective gaze positions are derived from the different spatial locations of pupillary and corneal reflections. Using a special calibration procedure, the subject's positions of gaze were continuously calculated by tracking the corneal reflection with respect to the centre of the pupil. The x- and y-coordinates of consecutive gaze positions were determined every 20 ms, and stored for further analysis. During the registration of eye movements, the subject sat in front of a screen which subtends 40° horizontally, and 32° vertically, with the head fixed at a distance of 140 cm. For the calibration procedure, which was carried out for each subject before the actual recording session, subjects were asked to fix, in a given order of succession, on small light spots (diameter 25 minutes of arc) arranged at the boundary of the projection screen in the form of a rectangle (six spots forming the upper and lower boundaries, one light spot in the centre). Fixation time at each stimulus position was at least 3 s. In the test session itself, eye movements were recorded while subjects silently read a text consisting of 61 words in nine lines; highly unfamiliar or foreign words were avoided. Words were printed in black against a light background (luminance 0.2 cd/m^2). Letter size was 1.0°, which allows the maximum reading rate (Legge *et al.*, 1985); letter width was 0.5°; spacing between letters was 0.2° and spacing between words 1°. Single lines were separated vertically by 2°. Illumination of the room was very low (1 lux). Subjects were asked to read the text silently, with no further instructions on how to proceed, and had to provide a report on the content of the text afterwards. Recording was started at the onset of text presentation and was ended after the subject indicated completion of reading. Eye movements were then analysed using a specially developed PC-based software program. For each subject, the individual calibration measurements were used as a basis for further data analysis. Successive points of measurement were combined into 'fixations' if they fell into a window of 1.5° of visual angle. The minimum duration of visual fixations was set at 100 ms. Eye movement data were quantitatively analysed with respect to reading time, number and amplitudes of saccadic eye movements, number and duration of fixations, and rates of repetition of saccades and of fixations. Eye movements were recorded while subjects read the text once. In normal subjects, the mean number of recorded eye movements (fixations $n+1$) varied between 36 and 82, in LH-patients it varied between 43 and 106, and in RH-patients between 58 and 120. The percentage of loss of data due to artefacts was, on average, 4% in normals (range 2–8%), and 9% in patients (range 4–15%). These artefacts resulted mainly from lid closures or saccadic eye shifts to positions outside the registration area. Recordings with >15% loss of eye movement data were not included in the analysis. Since each group (normal subjects, LH- and RH-patients) consisted of 25 subjects, the mean number of eye movements, which (after taking into account lost data) could eventually be analysed, was 1368 for the group of normal subjects, 1706 for the LH-group, and 2006 eye movements for the RH-group.

Statistical analysis of data

To test differences in reading performance and oculomotor parameters between patient groups and normal subjects, and within patient groups, a one-factorial multivariate analysis of variance (MANOVA) was performed. When significant group differences occurred, univariate F tests were performed to identify those variables which significantly contributed to the group differences. For these variables subsequent Scheffé *post hoc* tests were performed to detect those groups with significant differences in the variables. For testing the effect of treatment, ANOVA with a repeated measures design was performed. In the case of significant pre- versus post-treatment differences, tests with contrast were carried out to identify those variables which contributed to the treatment effects. For testing hypotheses, $P = 0.05$ was accepted as a nominal level of significance. In order to keep the type I error below this level, all *post hoc* tests (univariate F tests and tests with contrasts) were carried out at a $P < 0.05$ (level adjusted according to Bonferroni procedure).

Results

Hemianopia and reading eye movements

Figure 1 shows recordings of eye movements during reading in normal subjects (A and B), in patients with left-sided homonymous hemianopia and either 1° (C) or 5° visual field sparing (D), and in patients with right-sided homonymous hemianopia and 1° (E) or 5° field sparing (F). Normal subjects showed the typical regular staircase pattern of eye movements: fixations were followed by saccadic jumps, with incidental regressive saccades to the right or left. In contrast, patients with left-sided field loss showed eye movement patterns which were mainly characterized by the interruption of the saccadic jumps from the end of a line to the beginning of the next line, i.e. from right to left. In addition, the patient with only 1° of field sparing showed some irregularity in the left-to-right eye movements also. The deterioration in reading eye movements was especially pronounced in the two cases with right-sided hemianopia; the staircase pattern was broken, being substituted by many small saccadic jumps and regressive saccades. Fixation periods were considerably prolonged in some instances, amounting up to 1.5 s. Again, the degree of irregularity of the eye movement pattern depended on the extent of visual field sparing. The patient with 5° of sparing (Fig. 1F) showed less irregularity than the patient with only 1° of sparing (Fig. 1E). However, the reading eye movement pattern in the former patient appeared even more impaired than that in the patient with left-sided hemianopia and only 1° of sparing (Fig. 1C). Figure 2 shows the means for reading time (A), words per minute (w.p.m.) (B), number (C) and duration of fixations for the groups of normal subjects and of patients with LH- or RH-hemianopia. For all four parameters, both patient groups showed poorer results than normal subjects, the RH-group appearing worst of all. These patients required nearly threefold greater reading times, and their fixation times were, on average, ~75% longer than those of normal subjects. Both patient groups showed a high percentage of repetition of fixations; the corresponding data are 37% for the LH-group and 42% for the RH-group. For comparison, normal subjects repeated only 15% of their fixations. The mean first amplitude of eye movements from right to left (i.e. from the end of a line to the beginning of a new one) was 17.3° (SD = 3.5) in normal subjects and 14.7° (SD = 4.1) in RH-patients. In contrast, LH-patients used much shorter saccades to the left; their mean amplitude was 9.4° (SD = 5.2). The mean amplitudes of saccades to the right were 4.3° (SD = 0.7) for normal subjects, 4.1° (SD = 1.0) for LH-patients and 3.1° (SD = 0.4) for RH-patients.

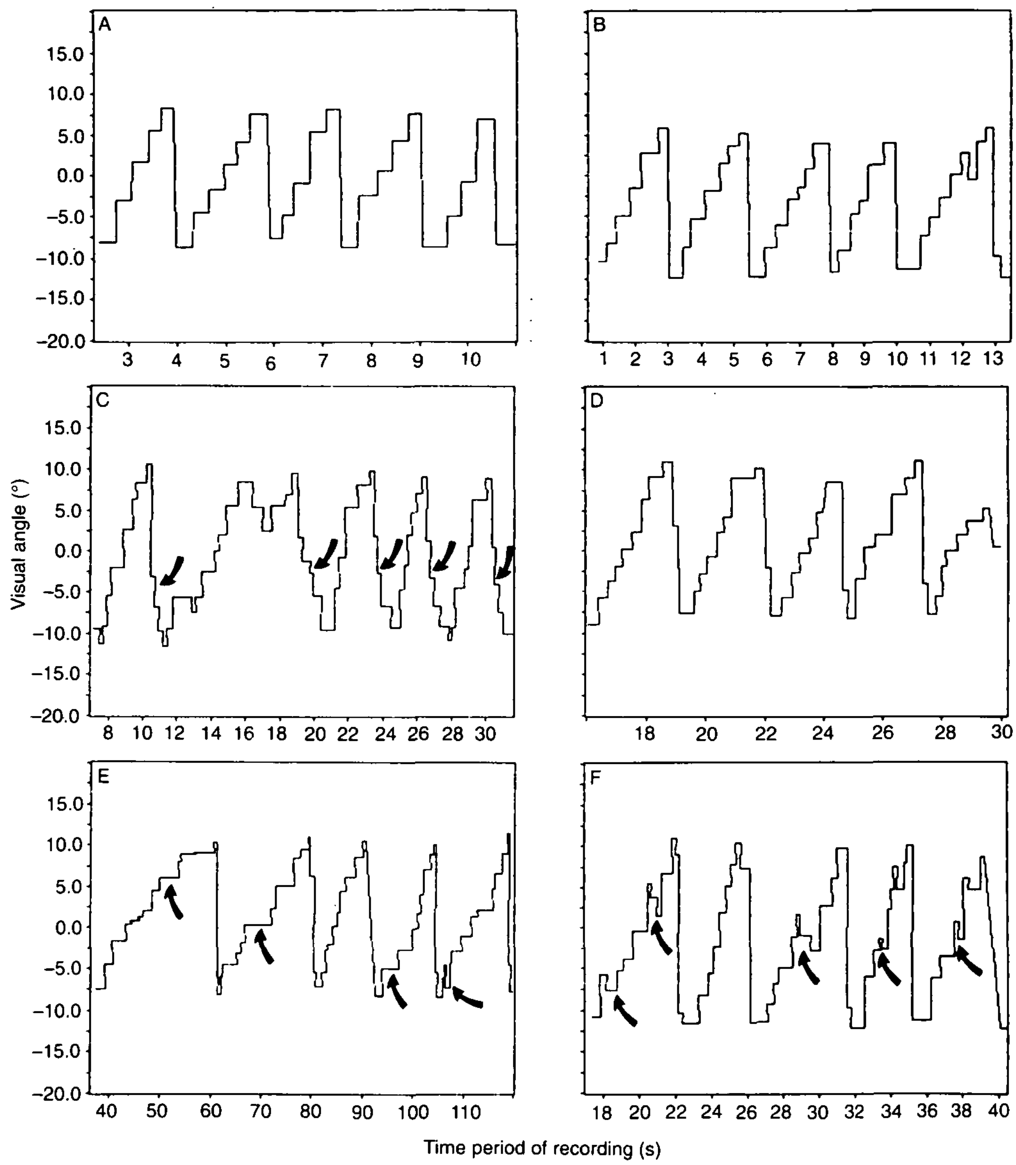

Fig. 1 Infra-red eye movement recordings in normal subjects (**A** and **B**) and in patients with LH- and RH-hemianopia with either 1° (**C** and **E**) or 5° visual field sparing (**D** and **F**). To improve clarity eye movement patterns during the reading of five lines are shown. *x*-Axis: time period of recording (in seconds); *y*-axis: horizontal extension of line (in degrees) (0 = centre; negative values = left; –20.0 = beginning of the line). Note interruption of saccades to the left in **C** and **D** (arrows) and regressive eye movements and prolonged fixations in **E** and **F** (arrows).

Statistical analysis (MANOVA) of eye movement parameters revealed significant differences between groups [Wilk's multivariate test of significance: approximately $F(24,118) = 8.42$, significance of $F < 0.0001$]. Univariate $F(2,70)$ tests established significant effects (all $P < 0.0001$) for reading time ($F = 25.07$), number of fixations ($F = 18.61$), repetitions of fixations ($F = 19.85$), durations of fixation ($F = 21.99$), number of saccadic eye movements to the left ($F = 21.75$) and to the right ($F = 18.86$), repetitions of saccades to the left ($F = 22.31$) and to the right ($F = 33.81$), and amplitudes of saccades to the left ($F = 20.97$) and to the right ($F = 18.59$). The outcome of group comparisons with the *post hoc* Scheffé test is shown in Table 1. Both LH- and RH-groups differed significantly from normal subjects with respect to the majority of eye movement parameters. The LH-patients showed significantly more saccades to the left, repeated significantly more saccades to the left and used smaller amplitudes of saccades to the left than did normal subjects. Whilst the RH-patients, in contrast, showed significantly longer fixation durations, a higher number of saccades and a higher rate of repetition of saccades to the right, and smaller amplitudes of these saccades than did normal subjects. The two patient groups differed significantly from each other in all parameters except for the number of fixations and the rate of repetition of fixations. Furthermore, a number of significant correlations between reading eye

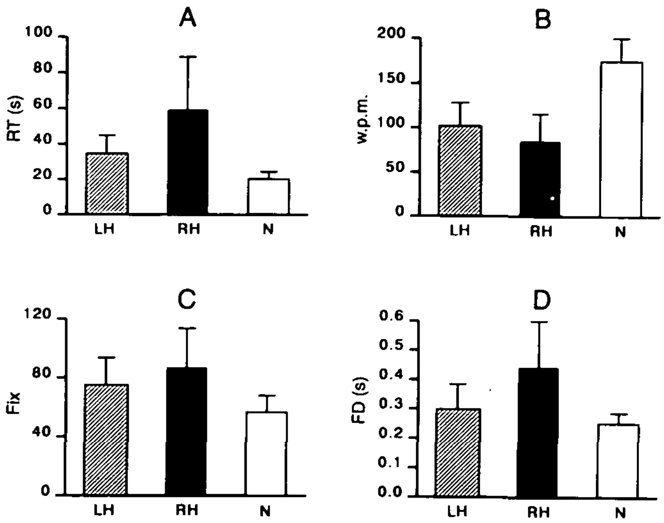

Fig. 2 Mean reading time (RT) (**A**), words per minute (w.p.m.) (**B**), mean number of fixations (Fix) (**C**) and mean duration of fixations (FD) (**D**) for a group of normal subjects (N), and of patients with LH- and RH-hemianopia, respectively. $n = 25$ in each group. Vertical bars indicate 1 SD.

Table 1 *Scheffé tests for testing mean differences between the groups N (normals), LH (patients with left-sided hemianopia),and RH (patients with right-sided hemianopia)*

	N–LH	N–RH	LH–RH
RT	*	*	*
Fix	*	*	n.s.
Fixr	*	*	n.s.
FD	n.s.	*	*
Sl	*	n.s.	*
Sr		*	*
Slr		*	*
Srr		*	*
Al	*	n.s.	*
Ar	n.s.	*	*

*$P < 0.05$; n.s. = not significant; RT = reading time; Fix = number of fixations; Fixr = repetition of fixations; FD = fixation duration; Sl = number of saccades to the left; Sr = number of saccades to the right; Slr = repetition of saccades to the left; Srr = repetition of saccades to the right; Al = amplitude of saccades to the left; Ar = Amplitude of saccades to the right. For explanation, *see* text.

movement parameters were found; these are summarized in Table 2. For all three subject groups, we found significant positive correlations between reading times and number of fixations. In the two patient groups, reading times were also significantly correlated with the number of repeated fixations and the duration of fixations.

The patients' ages and gender, as well as 'time since lesion', considered as covariates in MANOVA, did not significantly contribute to the differences in the various eye movement parameters between groups. In contrast, degree of visual field sparing contributed significantly ($P < 0.003$) to the differences between the two patient groups with respect to reading time ($t = -7.24$), number of fixations ($t = -6.58$), number of repeated fixations ($t = -5.67$), duration of fixations ($t = -4.33$), number ($t = -4.25$), amplitude ($t = 3.86$), and repetitions ($t = -3.83$) of saccades to the left, and number ($t = -4.10$) and repetitions of saccades ($t = -3.14$) to the right.

Parafoveal visual field and reading

The influence of visual field sparing on reading performance and reading eye movements was examined in more detail. Figure 3 shows reading time, words per minute, number of fixations, and eye movement parameters presented as a function of the degree of visual field sparing in LH- and in RH-patients. In both groups, reading time, number of fixations and duration of fixations decreased with increasing degree of field sparing; however, the effect was more pronounced in the RH-group. When visual field sparing was 4°, the LH-group was closer to normal subjects than were RH-patients. A similar picture emerged for the number of saccadic eye movements to the left and to the right, as well as for the corresponding amplitudes (Fig. 4). Finally, the percentages of repetition of fixations, and of saccades to the left and to the right (Fig. 5) also decreased in both groups with increasing field sparing, the reduction again being larger in the LH-group.

The influence of the factor 'degree of field sparing' on reading eye movement parameters was further examined statistically by separately calculating Pearson's correlation coefficients for LH- and RH-groups. In the LH-group, the following parameters were significantly correlated with field sparing: reading time ($r = -83$), number of fixations ($r = -0.74$), fixation repetitions ($r = -0.64$), number of saccades to the left ($r = -0.65$), number of saccades to the right ($r = -0.65$), and amplitudes of saccades to the left ($r = 0.59$). In the RH-group, we found significant correlations between visual field sparing and reading time ($r = -0.82$), number of fixations ($r = -0.70$), number of repeated fixations, ($r = -0.62$), duration of fixations ($r = -0.69$), number of saccade repetitions to the left ($r = -0.54$), and to the right ($r = -0.53$) ($P < 0.01$ for all r).

The interplay between saccadic amplitude and fixation duration

As discussed in the Introduction, the amplitude of the saccadic eye movements in the direction of reading, i.e. from left to right, is assumed to represent the size of the 'perceptual window' in reading, while fixation time may indicate its duration. We therefore examined, in more detail, for possible relationships between the duration of fixations and the amplitudes of saccades in the direction of reading, i.e. from left to right. In a first step, we used saccadic amplitude as a reference. Saccades were classified according to their size, and the respective numbers and durations of the following fixations were calculated. The following amplitude classes were used: 1–2.5°; 2.6–5.0°; 5.1–7.5°; 7.6–10°; 10.1–15°; 15.1–20°. We then classified, in a second step, the durations

Table 2 *Pearson's correlation coefficients between reading eye movement parameters for normal subjects, left-sided and right-sided hemianopia patients*

	Fix	Fixr	FD	Sl	Sr	Slr	Srr	Al	Ar
Normals									
RT	0.63*	n.s.	n.s.	n.s.	n.s.	0.60*	n.s.	n.s.	n.s.
Fix			–0.53*	n.s.	n.s.	0.82*	0.61		
Patients with left-sided hemianopia									
RT	0.67*	0.71*	0.66*	n.s.	0.64*	0.60*	n.s.	–0.52*	n.s.
Fix			n.s.	0.79*	0.81*	0.69*	n.s.	–0.51*	n.s.
Ali				–0.77*					
Patients with right-sided hemianopia									
RT	0.82*	0.67*	0.79*	n.s.	n.s.	n.s.	n.s.	n.s.	–0.64*
Fix			n.s.	0.69*	0.66*	0.90*	0.86*	–0.60*	–0.53*
FD									–0.58*

*$P < 0.05$; n.s. = not significant (two-tailed); RT = reading time; Fix = number of fixations; Fixr = repetition of fixations; FD = fixation duration; Sl = number of saccades to the left; Sr = number of saccades to the right; Slr = repetition of saccades to the left; Srr = repetition of saccades to the right; Al = amplitude of saccades to the left; Ar = Amplitude of saccades to the right. For further details, *see* text.

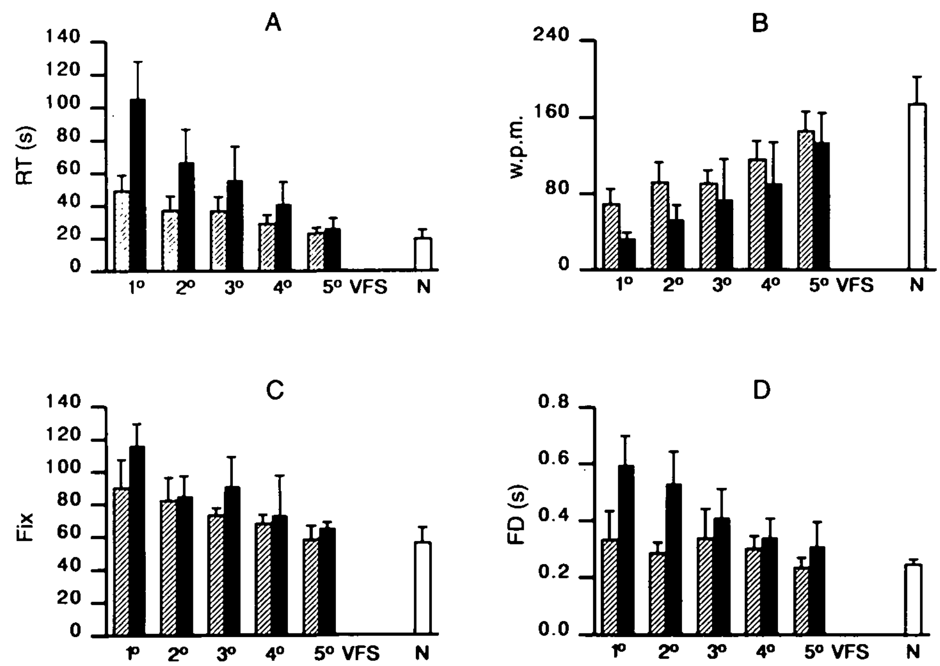

Fig. 3 Mean reading time (RT) (**A**), words per minute (w.p.m.) (**B**), mean number of fixations (Fix) (**C**) and mean duration of fixations (FD) (**D**) for patients with hemianopia plotted as a function of visual field sparing (VFS, in degrees). Hatched bars: LH-patients, filled bars: RH-patients. Corresponding data for the group of normal subjects (N) are also shown. Vertical bars indicate 1 SD. For details, *see* text.

of fixations, and calculated the number and amplitudes of the following saccades belonging to each class (100–200 ms; 210–300 ms; 310–400 ms; 410–500 ms; 510–750 ms; 760–1000 ms; 1100–1500 ms). Figure 6 shows the outcome of this type of analysis for the group of normal subjects. Figure 7 shows fixation durations plotted as a function of the amplitude of the foregoing saccadic eye movements and Fig. 8 shows saccadic amplitudes as function of the foregoing duration of fixations for the LH- and RH-patients.

Using saccadic amplitude as a reference, a decrease in the percentages of saccades with increasing amplitude, except for eye movements smaller than 2.5°, was found in normal subjects. Furthermore, normal subjects showed larger saccadic amplitudes before longer fixation durations. In the LH-group, we only found a decrease in the percentages of eye movements to the right with increasing field sparing. In the RH-group, the percentage of eye movements increased with increasing amplitude and decreased, in general, with larger field sparing. With respect to the duration of fixations following the saccadic eye movements, patients with left-

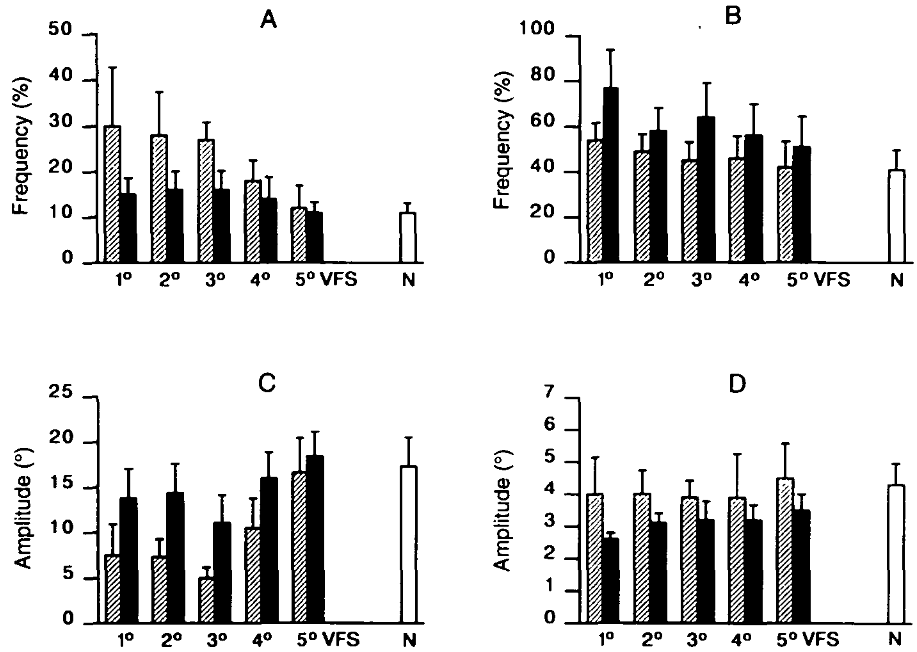

Fig. 4 Frequency (in %) and mean amplitudes of saccadic eye movements to the left (**A** and **C**) and to the right (**B** and **D**) plotted as a function of visual field sparing (VFS). Hatched bars: LH-patients, filled bars: RH-patients. N = corresponding data for normal subjects. Vertical bars indicate 1 SD. For details, *see* text.

sided visual field loss showed a pattern similar to normals, provided that field sparing was at least 4°. Mean durations of fixations depended on the degree of field sparing; the larger the amount of sparing, the shorter the duration of fixations. In contrast, patients with right-sided parafoveal field loss showed no systematic relationship between the amplitude of saccades to the right, and following fixation durations, except when field sparing was at least 5°. Again, mean duration of fixations decreased with increasing field sparing.

Using duration of fixations as a reference, we found a systematic decrease in eye movements with increasing durations of the foregoing fixations, in normal subjects, for saccades to the right (except for the class of 200 ms). Furthermore, mean amplitudes of saccades to the right increased for fixation durations longer than 400 ms. In the LH-group, only patients with at least 4° of parafoveal sparing showed a distribution of saccades similar to that found in normals. The RH-patients did not show any systematic relationship between fixation duration and the percentages of the following eye movements to the right, except for patients with 5° field sparing; the latter showed a pattern of decrease in the percentages of saccades to the right similar to those seen in normals and in LH-patients. With respect to the relationship between the duration of fixations and the amplitudes of following saccades, mean amplitudes to the right did not increase with increasing fixation duration in LH-patients; however, this parameter increased with increasing parafoveal sparing. In RH-patients, mean amplitudes to the right were always found to be smaller than the corresponding amplitudes of both the normal and the LH-groups, irrespective of fixation duration. However, mean amplitudes of saccades to the right increased with increasing fixation duration.

Statistical analysis (MANOVA) of eye movement parameters with the saccadic amplitudes as reference, a nested factor within the groups revealed a significant main effect of the factor 'group' [Wilk's multivariate test of significance: approximately $F(6,766) = 103.70$; significance of $F < 0.0001$], a significant main effect of the factor 'amplitude' [Wilk's test: approximately $F(12,1013) = 31.18$; significance of $F < 0.0001$], and a significant interaction effect of group by amplitude [Wilk's test: approximately $F(24,1111) = 3.58$; significance of $F < 0.0001$]. Univariate F tests revealed that the effect of the factor 'amplitude' is mainly due to number of saccades to the right [$F(4,385) = 39.86$, $P < 0.0001$], and to the fixation durations following saccadic eye movements [$F(4,385) = 67.63$, $P < 0.0001$]. The number of saccades to the right [$F(2,385) = 8.61$, $P < 0.0001$] and the duration of fixations following saccades to the right [$F(2,385) = 24.52$, $P < 0.0001$] contribute significantly to the effect of the factor 'group'. For the interaction group *x* amplitude, the number of saccades to the right [$F(8,385) = 6.11$, $P < 0.0001$] and the duration of subsequent fixations [$F(8,385) = 4.70$, $P < 0.0001$] differed significantly between groups. The outcome of group comparisons with the *post hoc* Scheffé tests is shown in Table 3A. The RH-patients showed significant differences as compared with the group of normal subjects and the LH-patients in most of the eye movement parameters. Significant differences between LH- and RH-groups for the number of

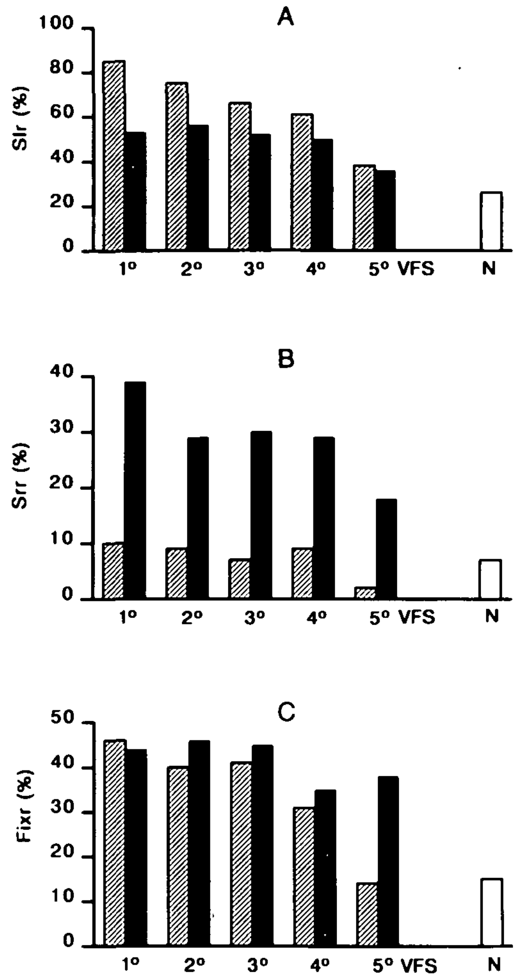

Fig. 5 Repetition (in %) of saccades to the left (Slr) (**A**), and to the right (Srr) (**B**) and of fixations (Fixr) (**C**) for patients with left- and right-sided hemianopia, plotted as a function of visual field sparing. For comparison, the data for normal subjects (N) are also shown. For details, *see* text.

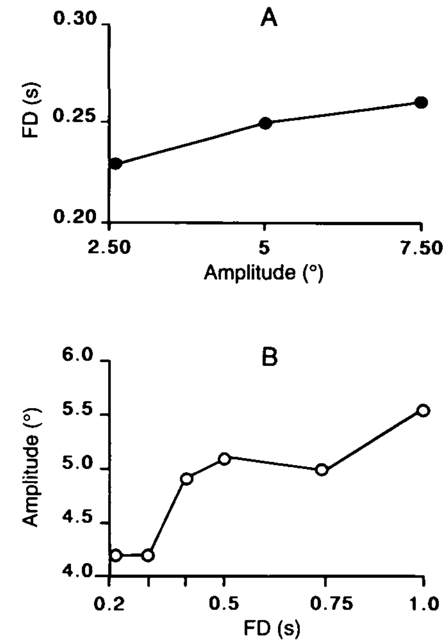

Fig. 6 Mean fixation durations (FD) plotted as a function of the amplitude of the foregoing saccades to the right (**A**), and mean amplitudes of saccades to the right as a function of the duration of the foregoing fixations (**B**), in a group of 25 normal subjects. Note the increase of durations of fixations with increasing size of saccadic amplitude in **A** and the enlargement of the saccadic amplitude with increasing fixation duration in **B**.

saccades to the right were only found in the 7.5° class. In addition, we found significant negative correlations (Pearson's correlation coefficients, two-tailed; $P = 0.001$) in normals and in patients with LH- and RH-hemianopia, between saccadic amplitudes and number of saccades ($r = -0.76$, $r = -0.79$ and $r = -0.47$, respectively), and the duration of the following fixations ($r = -0.57$, $r = -0.49$ and $r = -0.55$, respectively).

For 'fixation duration' as a reference, a nested factor within the groups revealed a significant main effect of the factor 'group' [MANOVA; Wilk's multivariate test of significance: approximately $F(6,766) = 81.11$, significance of $F < 0.0001$], a significant main effect of the factor 'fixation duration' [Wilk's test: approximate $F(12,1013) = 11.07$; significance of $F < 0.0001$], and a significant interaction effect of group by duration [Wilk's test: approximately $F(24,1111) = 2.37$; significance of $F > 0.0001$]. Univariate F tests for the factor 'fixation duration' revealed significant effects for the number of saccades to the right [$F(4,385) = 35.10$; $P < 0.0001$]. In addition, we found, significant group differences for the amplitudes of saccades to the right [$F(2,385) = 24.99$; $P < 0.0001$]. With respect to the factor 'group', the amplitudes of saccades to the right differed significantly between groups [$F(2,385) = 24.99$; $P < 0.0001$]. For the interaction group × fixation duration, the number of saccades to the right were found to differ significantly between groups [$F(8,385) = 7.02$; $P < 0.0001$].

Table 3B summarizes the significant differences, as revealed by *post hoc* Scheffé tests, between the three groups of subjects. The LH-patients did not differ from normals with respect to any of the examined variables. The RH-patients, in contrast, differed significantly from normal subjects with respect to the number of saccades to the right (except for 300 ms) and the amplitude of saccades to the right for the 200 ms and the 300 ms classes. We found, in addition, significant negative correlations (Pearson's correlation coefficients, two-tailed; $P = 0.001$) between the number of saccades to the right and the duration of the following fixations in normals ($r = -0.68$), and in patients with left-sided, but not right-sided, field loss ($r = -0.53$).

Discussion

The main results on the recordings of eye movements during text reading by normal subjects and by patients with either left- or right-sided hemianopia, can be summarized as follows. Reading time, and thus reading performance, in all three

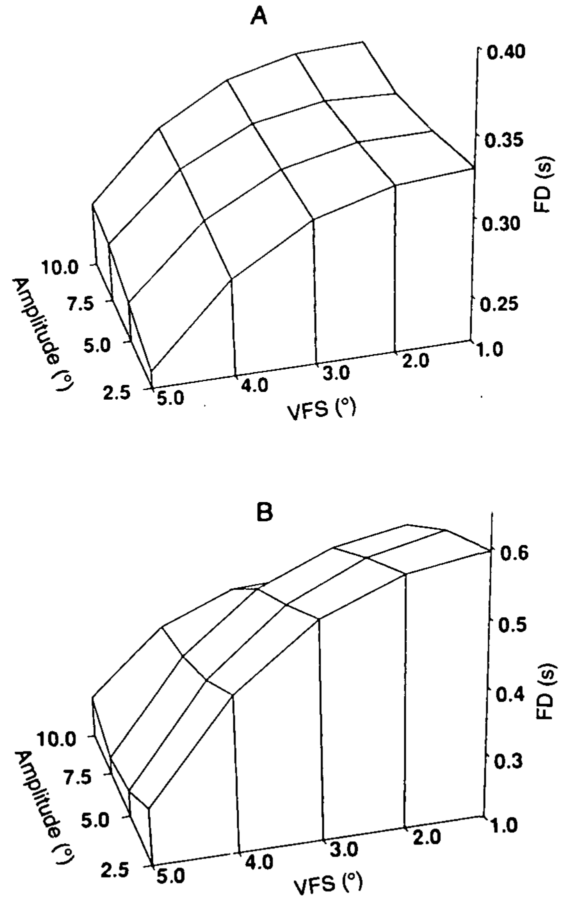

Fig. 7 Mean fixation durations (FD) plotted as a function of the amplitude of the foregoing saccade (in degrees) to the right for various degrees of visual field sparing (VFS) in LH- (**A**) and RH- (**B**) patients. Note the decrease of fixation durations as a function of field sparing, and the increase as a function of the amplitude of the foregoing saccade to the right in LH-patients for 4° and 5° of field sparing. In contrast, RH-patients show only a decrease of duration of fixations with increasing amount of field sparing. For further details, *see* text.

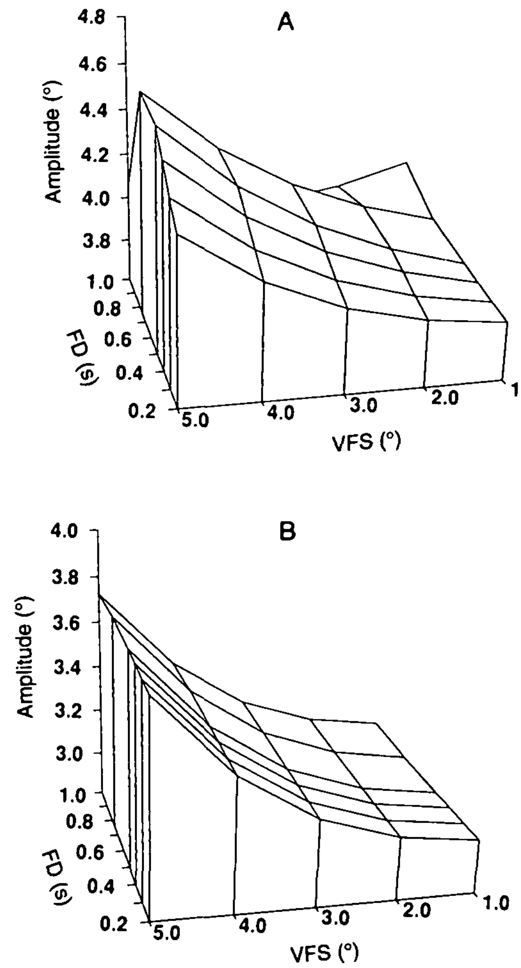

Fig. 8 Mean amplitudes of saccades to the right plotted as a function of the duration of the foregoing fixations (FD) for various degrees of visual field sparing (VFS) in LH- (**A**) and in RH- (**B**) patients. Note the enlargement of saccadic amplitudes with increasing field sparing and increasing duration of fixations in **A**. The RH-patients, in contrast, only showed an enlargement of saccadic amplitudes as a function of field sparing (**B**). For further details, *see* text.

groups of subjects, was mainly dependent on the number of fixations, the number of saccades to the left, and the duration of fixations. The fewer the fixations, the shorter their duration, and the fewer the regressive eye movements, the faster the processing of text information.

Parafoveal visual field loss impairs the pattern of reading eye movements in a typical way, whereby left-sided loss hinders patients to shift their gaze from the end of a line of text to the beginning of the next one, i.e. from right to left. The resulting impairment is characterized by a reduced amplitude of saccades to the left, an increased number of saccades to the left and a high percentage of repetitions of saccades and fixations to the left. The RH-patients, in contrast, find it difficult to shift their gaze in a systematic order in the direction of reading, i.e. from left to right. Their reading appears more impaired, and their eye movement pattern more disorganized, which can be characterized by a higher number of saccades to the right, with a high repetition rate, a reduced amplitude of these saccades and a considerably increased duration of fixations.

In attempting to identify those factors which significantly contribute to impaired reading behaviour, we could exclude age, gender, and time since lesion as significant factors, in our group of patients. The latter observation leads one to suggest that patients with hemianopic dyslexia either compensate very early for their parafoveal field loss, or do not regain normal, or nearly normal reading performance even several weeks after the occurrence of their hemianopia. Degree of visual sparing, however, was found to contribute significantly to the observed reading impairment. For both patient groups we found an improvement in reading performance as well as in the eye movement parameters with increasing parafoveal field sparing. The analysis of the eye movement pattern in the direction of reading, i.e. from left to right, using the saccadic amplitude as a reference for the

Table 3 *Summary of* post hoc *Scheffé tests*

(A)	2.5°	5.0°	7.5°	10°	
Sr	RH–N, LH	n.s.	RH–N, LH	LH–RH	
FDr	RH–N, LH	RH–N, LH	RH–N	n.s.	
(B)	0.1 s	0.2 s	0.3 s	0.4 s	0.5 s
Sr	n.s.	N–RH	n.s.	RH–N	RH–N, LH
Ar	n.s.	N, LH–R	N–RH	n.s.	n.s.

Summary of *post hoc* Scheffé tests using saccade amplitudes (A) and durations of fixation (B) as reference between groups for the numbers of saccades to the right (Sr), and for the durations of fixations preceding (A) saccades to the right (FDr), or to the amplitudes of the following saccades (B) to the right (Ar). N = normals, LH = patients with left-sided, RH = patients with right-sided parafoveal field loss. All P values = 0.001 (two-tailed); n.s. = not significant. RH–N, LH: the RH-group differs significantly from the N- and the LH-groups. For further details, *see* text.

following fixation durations, revealed that in normal subjects the larger the saccadic eye movement the longer the duration of the following fixation. Patients with left-sided field loss showed a similar relationship between saccadic amplitudes and the duration of the following fixations; in addition, fixation durations decreased with increasing visual field sparing. For RH-patients, no such relationship was found, except for when visual field sparing was at least 5°. However, the decrease in the duration of fixations was also associated with the extent of field sparing. Using the duration of fixations as a reference for the following saccadic eye movements, we found that mean saccadic amplitudes increased for fixation durations longer than 400 ms in normal subjects. No such relationship was found for LH-patients, except when field sparing was at least 4°. However, RH-patients showed, in general, smaller saccadic amplitudes. In contrast to the group of normals and the LH-group, we found no significant increase in the saccadic amplitudes with increasing fixation durations in the RH-group.

The results of our recordings in normals are in agreement with earlier reports which have shown that eye movements during reading are guided by both foveal and extrafoveal text information extraction (e.g., *see* Rayner *et al.*, 1978). Furthermore, our data underline the concept of a 'perceptual' window in reading, which can be characterized by its spatial (amplitudes of left-to-right saccades) and its temporal (duration of fixations) extents. The analysis of possible relationships between fixation durations and saccadic amplitudes, and vice versa, revealed interesting dependencies: the larger the saccadic amplitude, the longer the following duration of fixation, and the longer the foregoing fixation duration, the larger the following saccadic eye movement. This signifies that both the spatial as well as the temporal windows of the perceptual span are mutually dependent: the duration of fixation determines the amplitude of the following saccade, while the saccadic amplitude determines the following fixation duration. Thus, both parameters are not independently controlled but influence each other in a way which allows the acquisition of text information in a continuous and highly flexible way. As suggested by Rayner (1978) and O'Regan and Levy-Schoen (1987), eye movement patterns reflect cognitive processes in reading, but it is not just the duration of fixation which, according to the process-monitoring hypothesis (Rayner and McConkie, 1976), is affected by cognitive factors involved in text processing, but also the amplitude of the eye shifts to the right. Thus, both the temporal and the spatial size of the perceptual span in reading represent cognitive processes in reading.

Parafoveal visual field loss impairs reading in a way which can be predicted on the basis of the perceptual span in normals. Since the size of the perceptual span is smaller to the left, as compared to the right, from the fovea, patients with left-sided parafoveal field loss can be expected to be less impaired than patients with right-sided parafoveal field loss. This is in close agreement with our findings. Furthermore, visual field sparing was identified as the main factor underlying the impairment in the reading eye movement pattern; the smaller the degree of sparing, the more pronounced the disorder. This holds true for both the LH- and, more prominently, the RH-groups. The LH-patients with only 1° or 2° of sparing were superior in their reading performance as compared to RH-patients with 4–5° sparing. Patients seem to try to compensate for their parafoveal field loss mainly by changing their oculomotor behaviour. In the case of left-sided parafoveal field loss patients use a safe, but slow, step-by-step strategy in shifting the eyes to the left. Patients with right-sided parafoveal field loss show many more saccades, which are typically smaller in size, thereby increasing their fixation periods. In addition, these patients show a high rate of regressive saccades, indicating the return to that part of a word which has already been perceived, which is, of course, an unproductive attempt to compensate for the field loss. These observations resemble those described in earlier reports, using electro-oculography for the recording of reading eye movements (Mackensen, 1962; Gassel and Williams, 1963; Meienberg *et al.*, 1986).

In addition to the analysis of these qualitative and quantitative alterations of the pattern of reading eye movements, we examined the effect of the parafoveal field loss on the spatial and temporal 'size' of the perceptual span in greater detail. In normal subjects, the mean spatial extent was, in our testing conditions, 4.26°, its mean temporal extent was 243 ms, both values being in close agreement to those reported in the literature (e.g. Yarbus, 1967; McConkie *et al.*, 1985). In addition, we found a systematic relationship between the duration of fixation and the amplitude of the following saccade, and between the saccadic amplitude and the duration of the following fixation, indicating that both the temporal and the spatial extents of the perceptual window are under 'higher-order' control. In LH-patients, the spatial extent of the perceptual span ranged from 4.02° (1° field sparing) to 4.52° (5° of sparing), while its temporal extent ranged from 332 to 234 ms. In RH-patients, in contrast, no systematic relationships were found between saccadic amplitudes and fixation durations. The spatial extent of their perceptual span ranged from 2.58° (1° of sparing) to 3.46° (5° of sparing), the temporal extent from 596 to 308 ms. These changes indicate that the higher-order organization of the reading eye movement pattern has been lost, or was at least severely impaired in this group of patients. Poppelreuter (1917—translated 1990) has called this disorder 'disturbance of reading coordination', whereby 'successive eye shifts are no longer in the order dictated by the visual information, but occur irregularly' (p. 224). Based on our results, it can be added, that not only the 'bottom-up', but also the 'top-down' guidance of reading eye movements is impaired in cases with parafoveal visual field loss, possibly because top-down regulation cannot come into play in the absence of the parafoveal visual field.

Oculomotor reading patterns before and after treatment of hemianopic dyslexia

There are several possibilities to study changes in the oculomotor reading pattern in normals, among them manipulations of physical text properties (Levy-Schoen, 1981; Legge *et al.*, 1985), and of the size of the perceptual window, either with respect to its temporal (McConkie *et al.*, 1985) or spatial extents (Ikeda and Saida, 1978; Rayner and Bertera, 1979). In patients suffering from unilateral postgeniculate damage to the visual pathway, nature has introduced another 'manipulation', if this expression is permitted, namely the loss of parafoveal visual field, whereby the cognitive and semantic aspects involved in reading are spared. Thus, these patients offer a unique opportunity to study oculomotor adaptation processes in reading. The treatment of reading impairment is one of the major issues in neuropsychological rehabilitation of patients with homonymous visual field loss, and sparing of <5° of the parafoveal visual field (Zihl, 1994). Patients with hemianopic dyslexia are reported to adapt themselves somehow to the field loss, showing a decrease in the degree of reading impairment (e.g. Gassel and Williams, 1963). In a larger series of patients with homonymous field loss (n = 462; Zihl, 1994) we found that parafoveal field sparing was <4° in ~75% of patients. The majority of these patients (92% of the RH-group, and 74% of the LH-group) were found to have difficulties with reading as a result of the parafoveal field loss. There exists a specific, scientifically proven, and standardized method to improve reading in these patients (Zihl *et al.*, 1984; Kerkhoff *et al.*, 1992). We used this method to treat patients with parafoveal hemianopic field loss, and recorded eye movements before and after treatment. Time since lesion and degree of visual field sparing were kept constant, and patients with changes in the visual field border after treatment (Kerkhoff *et al.*, 1992) were excluded. The analysis of reading eye movements before and after treatment allowed us to identify those eye movement parameters which were changed, as well as gain an insight as to the strategy of oculomotor adaptation to overcome the parafoveal field loss.

Patients and methods for 'after treatment' investigations

A subgroup of 20 patients (eight females, 12 males) with LH- or RH-hemianopia (n = 10 in each group) was selected for this part of the study. Mean age was 39 years (range 21–53) in the LH-group, and 37 years (range 19–54) in the RH-group. Time since first examination of visual field and of reading was ~3 weeks in two groups (mean 3.3 weeks; range 3–5 weeks). Visual field sparing did not exceed 3° in both groups; mean sparing in the LH-group was 2.1° (SD = 0.9) and 1.9 (SD = 0.9) in the RH-group.

The method of treatment was mainly based on the reorganization of the reading eye movement pattern. Briefly, patients with left-sided parafoveal field loss were forced to shift their gaze to the beginning of every word in a line of text which moved slowly from right to left (i.e. in the direction opposite to that of reading). Patients with right-sided parafoveal field loss, on the other hand, were instructed not to read a word before shifting their gaze to the end of the word. Thus, both groups were forced to intentionally perceive the whole word before reading it. [For details of the method of treatment, *see* Zihl (1990) and Kerkhoff *et al.* (1992).] Patients with LH-hemianopia required, on average, 11 training sessions (range 8–16) to regain a reading performance in the range of age-matched normal subjects, as assessed with a standardized reading test (Zihl *et al.*, 1984). For patients with RH field loss, 22 sessions (range 9–29) were needed to improve reading to about the same degree. Since two sessions were carried out daily, the period of practice lasted 1–2 weeks in the LH-group, and 2–3 weeks in the RH-group.

Results

Neither the LH- nor the RH-groups showed any change in reading performance between the first time of testing and the beginning of treatment. When tested for the first time, the group of LH-patients required, on average, 4.3 min (SD = 0.92; range 3.5–5.7); the corresponding numbers before treatment, using a parallel version of the standard reading test, were 4.1 min (SD = 0.79; range 3.3–5.8). Mean reading time in RH-patients at the first time of testing was 7.3 min (SD = 2.1; range 4.8–11.4); before treatment, these patients required, on average, 7.4 min (SD = 2.2; range 4.6–11.3). Thus, reading times did not show any essential changes in the period between the first time of testing and the testing before treatment. Before training, LH-patients showed a mean error rate (mainly omissions) of three errors (range 0–6), while RH-patients made, on average, nine errors (range 4–16). After practice, none of the patients showed reading errors. Reading speed was considerably reduced before training in both groups; LH-patients showed a rate of 76 w.p.m. (SD = 25) before training and RH-patients 53 w.p.m. (SD = 31). After treatment, the corresponding values were 113 (SD = 29) for the LH-group and 96 (SD = 46) for the RH-group. For comparison, the rate of words per minute in normals, reading the same text, was 174 (SD = 29). It is important to note that this improvement cannot be attributed to a change in the visual field extent, since none of the patients showed any major change in the parafoveal field border after treatment.

Figure 9 shows eye movement recordings for two patients with LH- and two patients with RH-hemianopia, with either 1° or 3° of parafoveal field sparing, before (A1, B1, C1, D1) and after treatment (A2, B2, C2, D2). All patients showed a more systematic eye movement pattern after treatment. In Fig. 10, mean reading times, and numbers and durations of fixations are shown for the LH- and the RH-groups, before and after treatment, and for the group of normals for comparison. After treatment, there was a pronounced reduction in reading time, numbers of fixations, and duration of fixations in the patient groups. The performance of the LH-group was now in the range of the corresponding data of normal subjects, while the RH-group showed poorer results. Concerning the rate of fixation repetitions before treatment, LH-patients repeated an average of 42% of fixations and RH-patients 49% of fixations; after treatment, the corresponding percentages were 32% and 33%.

Statistical analysis (MANOVA) revealed a significant treatment effect for both the LH- [Wilk's multivariate test of significance: approximately $F(5,5) = 10.32$, significance of $F = 0.012$] and the RH-groups [approximately $F(5,5) = 21.24$, significance of $F = 0.002$]. Univariate F tests showed that the treatment effect for the LH-group is mainly due to reading time [$F(1,9) = 17.89$], number of fixations [$F(1,9) = 19.15$)] number of repeated fixations [$F(1,9) = 16.47$], number of saccades to the left [$F(1.9) = 32.61$] and to the right [$F(1.9) = 29.98$] and for the amplitude of saccades to the left [$F(1,9) = 76.17$] ($P < 0.002$ for all Fs). For the RH-group, the treatment effect is due to reading time ($F = 37.17$), number of fixations ($F = 60.14$) and fixation repetitions ($F = 45.00$), and the duration of fixations ($F = 11.99$), the number of saccades to the left ($F = 24.50$), and their repetition rate ($F = 15.61$), the number of saccades to the right ($F = 24.50$), repetitions ($F = 16.28$), and amplitudes of saccades to the left ($F = 35.43$) and to the right ($F = 191,12$) (P-values for all Fs < 0.007).

Furthermore, we again used the amplitudes of saccades to the right as reference for the duration of the following fixations, and the durations of fixations as a reference for the amplitudes of the following saccades to the right. The same classes of saccadic amplitudes and of fixation durations were used as in the earlier analysis (*see* The interplay between saccadic amplitude and fixation duration); results are shown in Fig. 11. Using saccadic amplitudes as reference (Fig. 11A and B), we found, in both groups, a reduction of the duration of fixations, but both patient groups showed, in general, higher fixation durations even after treatment. With the duration of fixations as reference (Fig. 11C and D), neither group of patients showed an increase in saccadic amplitudes with increasing durations of fixation; however, both groups showed slightly larger saccades after treatment.

Statistical analysis (MANOVA) of eye movement parameters with the saccadic amplitudes as reference revealed significant pre- versus post-treatment differences in the LH-group for the amplitude class of 5° [Wilk's multivariate test of significance; approximately $F(2,8) = 9.42$, significance of $F = 0.008$]. For the RH-group, significant differences were found for the amplitude classes of 2.5° [approximately $F(2,8) = 11.84$ significance of $F = 0.004$], and of 7.5° [approximately $F(2,8) = 9.73$, significance of $F = 0.007$]. Using fixation durations as reference for the amplitude of the following saccadic eye movements to the right, MANOVA established no significant pre- versus post-treatment differences for the LH-group in either class of fixation durations. For the RH-group, a significant difference was found for the duration classes of 400 ms [Wilk's multivariate test of significance; approximately $F(2,8) = 9.57$, significance of $F = 0.008$], and of 750 ms [approximately $F(2,8) = 7.66$, significance of $F = 0.01$].

Discussion

Summarizing the results on the effect of treatment on the pattern of reading eye movements in patients with parafoveal field loss, there is a clear relationship between the improvement in reading performance and changes of eye movement parameters. In both LH- and RH-groups, the number of fixations and their repetitions, the number and rate of repetition of saccades to the left and to the right, were significantly lower after treatment. Furthermore, LH-patients showed a significant increase in the amplitude of their leftward-saccades, while RH-patients displayed significantly enlarged saccades to the left and to the right; in addition, the duration of their fixations was significantly reduced after treatment. The effective adaptation of the oculomotor reading pattern to the parafoveal field loss was also characterized by changes in the size of the perceptual spans. In LH-patients, the mean spatial extent of the perceptual span increased from 3.75° before, to 4.03° after, treatment, and its mean temporal extent decreased from 319 ms to 294 ms. In RH-patients,

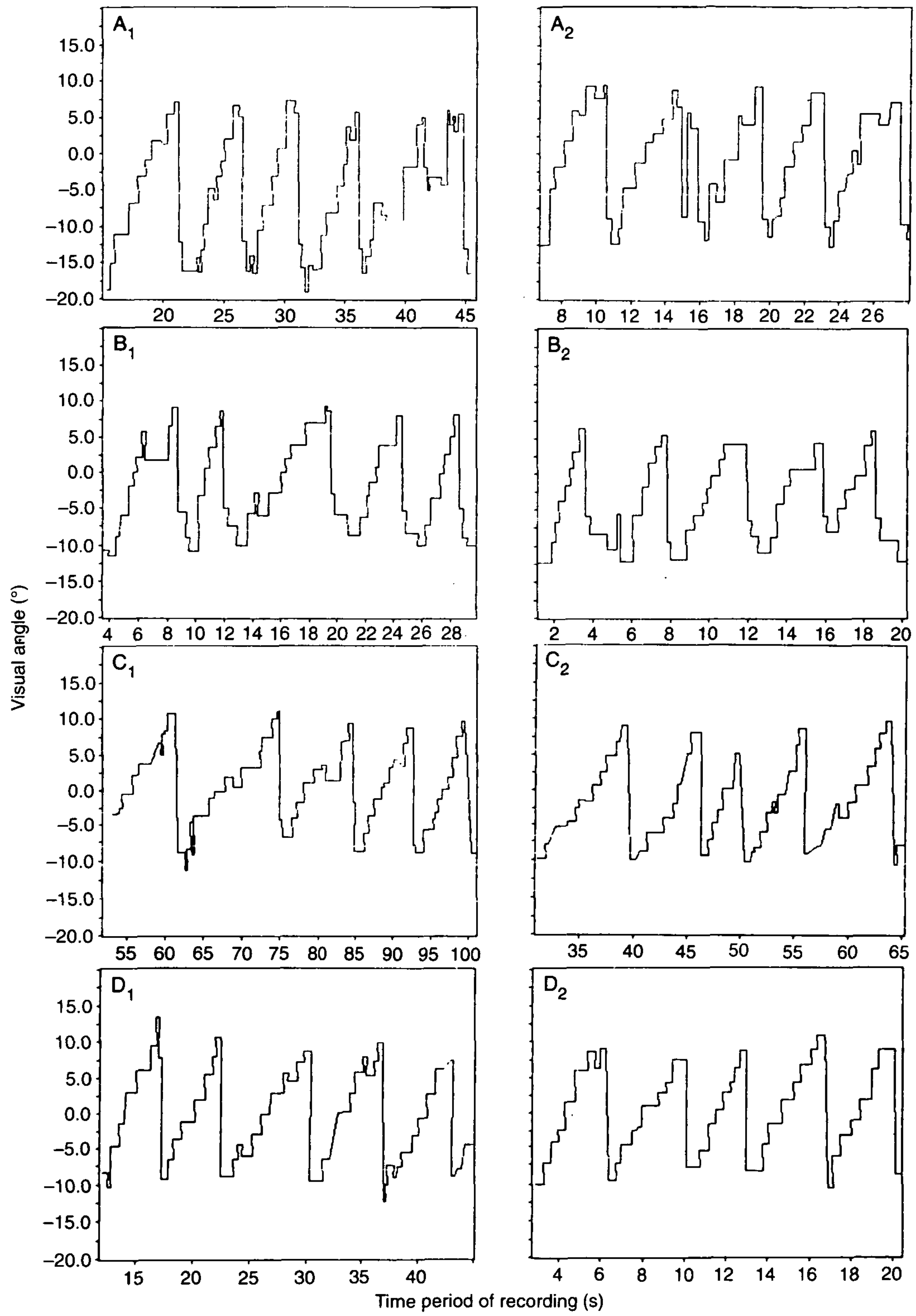

Fig. 9 Eye movement recordings in patients with hemianopic dyslexia before (1) and after treatment (2). **A** and **B**, Patients with left-sided hemianopia and 1° and 3° field sparing; **C** and **D**, patients with right-sided hemianopia and 1° and 3° field sparing. To improve visibility eye movement patterns during the reading of five lines are shown. *x*-Axis: time period of recording (in seconds); *y*-axis: horizontal extension of line (0 = centre; negative values = left; –20.0 = beginning of the line). Note reduction of regressive eye movements and shortening of fixation durations after treatment.

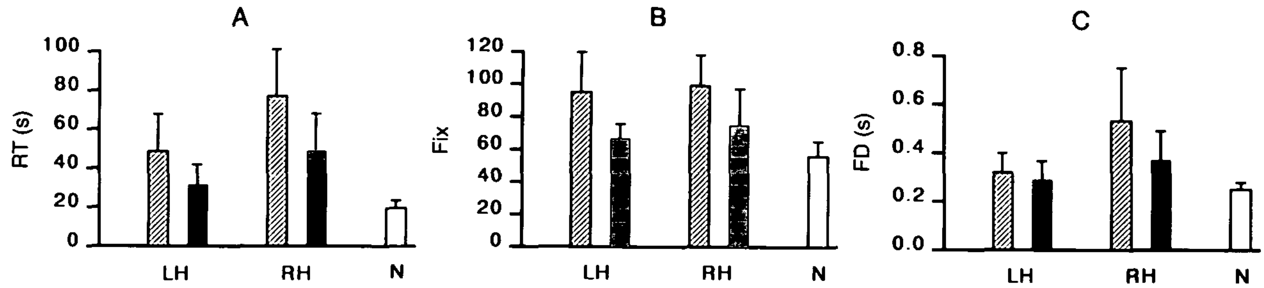

Fig. 10 Mean reading time (RT) (**A**), number of fixations (Fix) (**B**), and duration of fixations (FD) (**C**) for patients with left (LH) and right (RH)-sided hemianopia before (hatched bars) and after (filled bars) treatment. For comparison, data from normal subjects (N) are shown. Vertical bars indicate 1 SD.

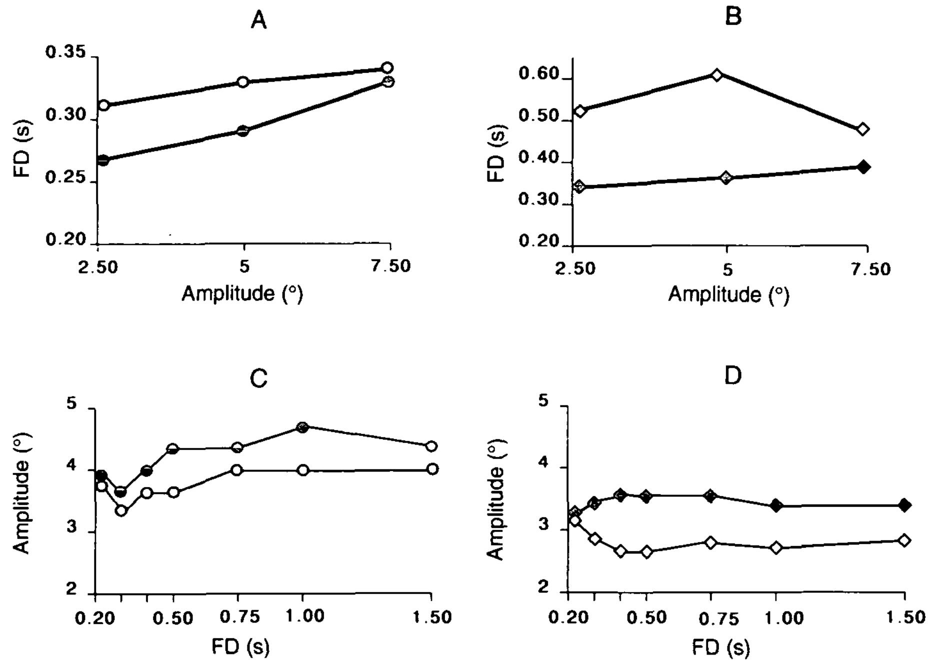

Fig. 11 Mean fixation duration (FD) plotted as a function of the amplitude of foregoing saccades to the right for LH- (**A**) and RH- (**B**) patients before (open symbols) and after (filled symbols) treatment. In **C** and **D**, mean amplitudes of saccades to the right are plotted as a function of the duration of the foregoing fixations (FD) for LH- (**C**) and for RH- (**D**) patients before (open symbols) and after (filled symbols) treatment. Note the absence of increase in fixation durations and saccadic amplitudes in RH-patients (**B** and **D**) before and after treatment, in contrast to LH-patients (**A** and **C**).

the mean spatial size of the span increased from 2.79° before, to 3.74° after, treatment; its mean temporal extent decreased from 526 ms to 372 ms. For comparison, the corresponding mean values in normals were 4.26° for the spatial, and 243 ms for the temporal extent of the window.

As for relationships between saccadic amplitude and duration of following fixations, we found a general decrease of fixation durations in both groups after treatment. However, this decrease only reached statistical significance for durations belonging to the 5° amplitude class in the LH-group, and for durations belonging to the amplitude classes of 2.5° and of 7.5° in the RH-group. For amplitudes of saccades to the right, no significant enlargement in the LH-group was found; however, such enlargement was observed for the 400 ms and 750 ms classes in the RH-group. Thus, the main treatment effect appears to be based on effective changes in the oculomotor pattern in reading, whereby some kind of 'normalization' in the relationships between saccadic amplitudes and fixation durations occurred. It should be added, however, that, despite a significant improvement in reading performance in the RH-group, reading eye movement parameters remained inferior, even after treatment, as compared with those of normal subjects.

The question of whether the improvement in reading was related to treatment, or whether it would have also occurred without (specific) practice, deserves some comment. The majority of patients with parafoveal field loss and associated reading difficulties have been reported to remain impaired even years after the occurrence of the field loss (Gassel and Williams, 1963), suggesting that, in the absence of field recovery, spontaneous compensation for the parafoveal field loss is the exception rather than the rule. In fact, all of our patients have tried to regain reading skills on their own, or were to do so with help from relatives, but with no substantial improvement. For this reason we used a treatment design wherein every patient served as his or her own control. Since we could not observe any change in reading performance in the period between the first time of testing and the beginning of the treatment (3–5 weeks), on the basis of significant improvement after treatment, which lasted 1–3 weeks, it seems reasonable to assume that systematic practice at least facilitated the process of oculomotor compensation. Furthermore, it would be difficult to argue that spontaneous improvement did not take place within 9–11 weeks, but then occured spontaneously, within the next 2 or 3 weeks.

General discussion

Our data support and extend the previous assumptions about the guidance of eye movements during text apprehension, and the presumed interactions between vision, cognition and the oculomotor system. The essential parameters by which these interactions can be characterized, are the duration of fixations and the amplitude of saccades in the direction of reading, i.e. from left to right. In normals, and in both patient groups with parafoveal field loss, the rate of repetitions of fixations was negatively correlated (significantly) with the duration of fixations, indicating an inverse relationship between the number and duration of fixations. The amplitudes of saccades to the right and the durations of fixations may represent the spatial and temporal size of a perceptual window which is 'moved' from left to right to extract more or less continuous text information, and can thus be applied to the description of the perceptual span in reading. The spatial, as well as the temporal, extents of the window are systematically interdependent: the longer the duration of a fixation, the larger the following saccade, and the larger the saccadic amplitude, the longer the following fixation. A similar dependency has been reported for the letter span in a continuous letter search paradigm, but only with respect to fixation durations following saccades to the right (Nattkemper and Prinz, 1987). As shown by other authors, the duration of a fixation can be influenced by various factors, including the size and physical properties of letters, difficulty in comprehending the text, or frequency and syntactic complexity of the foveal word (for a review, *see* Pollatsek and Rayner, 1989). This variability in fixation durations favours the assumption that fixation periods indicate visual-cognitive aspects of text processing, and cannot be explained in terms of saccadic initiation times. Although the latter are also in the range of 200 ms, they are under the control of the saccadic system alone (for a review, *see* Leigh and Zee, 1991). This argument is further supported by the effect of treatment: major changes were found with respect to the duration of fixations and the saccadic amplitudes. The LH-patients mainly showed a decrease in the fixation periods, whereas RH-patients showed both an increase in the saccadic amplitudes and a decrease in fixation durations. Thus, the adaptation of the eye movement pattern to the parafoveal field loss was mainly one of adapting the spatial and temporal size of the perceptual, and of course attentional window to the field loss. This implies, that, by way of top-down regulation, higher-order processes can influence the size of the perceptual window in a very efficient way, such that the lost parafoveal field region can be successfully substituted. These higher-order processes may be assumed to be both attentional and cognitive in nature (McConkie and Zola, 1987; Rayner and Pollatsek, 1987): attentional, because patients have to shift their attention to text information within the lost parafoveal field region, and cognitive, because they learn how to use their earlier acquired reading strategy. This strategy also includes cognitive 'supervisory' processes, which normally also appear to require the parafoveal visual field. The significant reduction in amplitude of rightward saccades in RH-patients before treatment, and their enlargement after treatment, may be taken as evidence for the substitution of the parafoveal visual field right from the fovea by an oculomotor process which is normally guided by this portion of the visual field. When parafoveal word information is withheld in normal subjects, reading rate decreases sharply (for a review, *see* Inhoff, 1987). Unfortunately, how much practice would be required for normal subjects to regain their normal reading performance, and what the main compensatory mechanism(s) might be, are unknown. This experimentally provoked impairment in normal subjects can be explained in two ways. According to the 'visual salience' hypothesis, the magnitude of the benefit of the parafoveal text extraction is a function of the visibility of the parafoveal letter string, i.e. takes place at a sensory-perceptual level. Alternatively, the word-structure hypothesis suggests that a specific type of information is sought from the parafoveal text which is fed into the mental lexicon where it is compared with the represented word(s). According to this more 'cognitively driven' hypothesis, the 'contacted representation' of a given word could then be elaborated during the following fixation (*see* Rayner, 1978). Observations in cases with 'real loss' of the parafoveal field due to postgeniculate brain damage, however, indicate that these two hypotheses are not mutually exclusive, but rather complement each other. Before treatment, many RH-patients showed a typical pattern of regressive saccades, i.e. they shifted their gaze backwards to that portion of a word which they had already perceived. Thus, they could not feed text into the mental lexicon, and elaboration of the meaning of the partly perceived word was impossible. After treatment, these patients shifted their gaze first to the end of each word, and could then also understand the text they had perceived. It seems that under normal circumstances one requires extrafoveal information to make contact with the representations of words in the mental lexicon, and thereby to elaborate the meaning of the text. Our data, therefore, do not support a dominant role for the word-structure hypothesis

(Inhoff, 1987), but can best be interpreted in the framework of the process-monitoring hypothesis (Rayner and McConkie, 1976; Rayner, 1978) according to which fixation durations are affected by cognitive processing occuring during the period of fixation. The amplitude of the eye movements in the direction of reading can, of course, also be 'affected' by cognitive processing. We would, therefore, propose an extension of the process-monitoring hypothesis to include saccadic amplitude, i.e. to both the temporal and spatial size of the perceptual window. As a superior mechanism which coordinates and 'supervises' visual-cognitive interaction, a 'visual attention control subsystem' (Shallice, 1988) may be operative in a very flexible way and may determine the size and locus of the perceptual window over which text information is integrated and apprehended. Our results indicate that reading is characterized by non-random information sampling within a continuously moving perceptual window, which can be assessed by measuring fixation periods and amplitudes of saccades to the right. Parafoveal visual field loss impairs this special type of integrated information processing, such that spatial and temporal coherence of text processing is disrupted. It appears that the integration of visual information across field regions which may represent a fundamental principle in spatial integration of information processing (Zeki, 1993), is the main impairment in hemianopic dyslexia. In reading, information from the parafoveal and foveal field regions has to converge topically in order to be integrated across fixations. Our data on the effects of treatment indicate that topical convergence can, in the absence of information from the primary visual cortex, be at least partly achieved by reorganization of the oculomotor reading pattern. This reorganization is undoubtedly enhanced and supported by attentional and cognitive top-down influences. Eye movement patterns do reflect the cognitive processes occuring in reading (Rayner, 1978) and allow a more direct assessment of visual-cognitive interactions. Detailed study of the pathological case does not only allow assessment of the consequences of a focal brain lesion on a complex function, but also allows the measurement of adaptive processes, e.g. following treatment. The analysis of processes of adaptation may help to understand better interactive processes between various mechanisms which underlie complex abilities like reading, at the sensory, perceptual and cognitive processing levels.

On the anatomical basis of hemianopic dyslexia

Although hemianopic dyslexia was described in detail ~90 years ago (Mauthner, 1881; Wilbrand, 1907), the anatomical basis for this disorder has not been analysed so far. Both Mauthner and Wilbrand, as well as Poppelreuter (1917—translated 1990) and Gassel and Williams (1963), hypothesized that the loss of the parafoveal visual field is the main cause for this type of reading impairment. This assumption is supported by the observation that in the majority of patients suffering from hemianopia, field sparing is <4–5°, and that these patients show, as a rule, impaired reading. There are, however, exceptions (10 out of 35 cases, or 29% in the study of Gassel and Williams, 1963; eight out of 50 cases, or 16% in our group) which contradict such a general conclusion.

In our group, reading performance of patients with damage restricted mainly to the calcarine cortex ($n = 8$; *see* Fig. 12A and B) was in the range found for normal subjects, at least 4 weeks after the occurrence of the hemianopia (Table 4). This does not necessarily mean, however, that their reading performance was not at all affected by the parafoveal field loss. Six patients reported impaired reading after stroke, but all of them could eventually regain, as one patient put it, a 'fairly good' reading performance allowing them to return to their jobs and to resume their daily activities. Compared with their premorbid level, however, all but one patient reported inferior reading at the time of first testing, which is in accordance with the reduction of reading performance (12%) when compared with the performance of normal subjects. There is no doubt, however, that reading abilities were restored in these patients without systematic intervention. A second group of patients ($n = 22$) can be classified as having moderately impaired reading (Table 4). Their mean reading performance was ~38% lower than that of normal subjects. All patients in this group reported impaired reading after the occurrence of the hemianopia, with only slight improvement over time. These patients typically showed larger lesions involving the striate cortex and, partially, the occipital white matter also (Fig. 12C and D). The third group of patients ($n = 20$) showed severe reading impairment, which was in the range of only 32% of normal performance (Table 4), resulting in a pronounced visual handicap in their vocational and everyday-life activities. In addition, these patients showed extensive involvement of the ipsilateral occipital white matter (Fig. 13) and, in seven cases, of the ipsilateral posterior thalamus also (Figs 13 and 14).

In their morphological study on unilateral posterior cerebral artery infarctions, Kleihues and Hizawa (1966) found infarctions comprising the entire calcarine cortex in 47% of 35 cases; in many cases, the occipital white matter was also affected. On the basis of CT-analysis, Hebel and von Cramon (1987) reported calcarine infarctions in 23% of cases out of a group of 159 patients; five patients (14% in this subgroup) also showed lesions of the ipsilateral thalamus. These authors also pointed out that pure calcarine infarctions typically spare the occipital white matter. In our group of 50 patients, 16% showed posterior cerebral artery infarctions without damage to the ipsilateral thalamus or the occipital white matter. However, one should be cautious in determining the size of brain damage based on MRI or CT since these imaging methods may underestimate the extent of the lesions. Cerebral perfusion and PET studies have shown that changes in glucose metabolism may occur in the undamaged ipsilateral thalamus and visual association areas after unilateral damage to the optic radiation (Bosley *et al.*, 1985), and subcortical

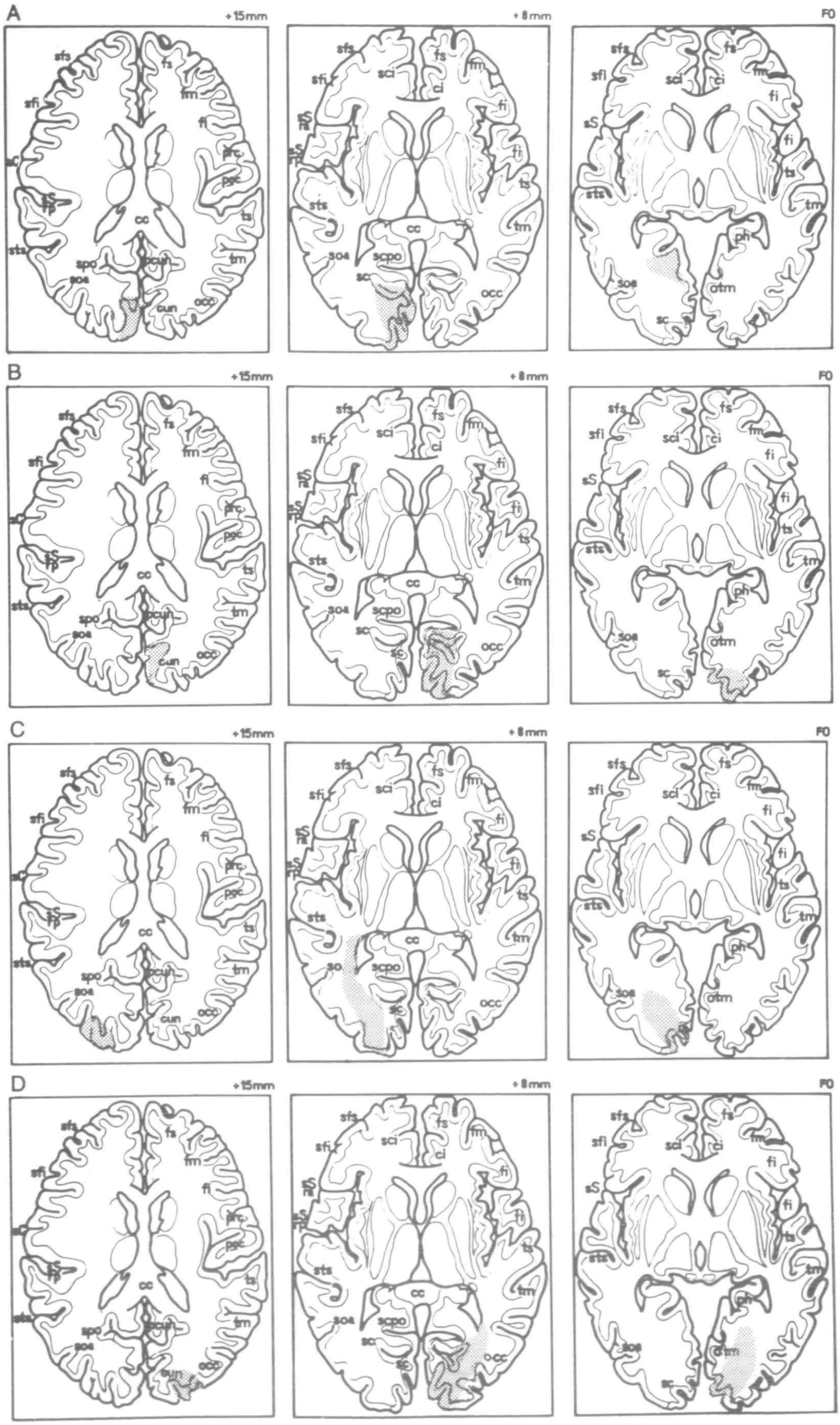
A
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Table 4 *Mean reading performance*

Group	w.p.m.	Range	Percentage performance
N	174.2	139–237	100
A	154.2	143–179	88.5
B	107.7	88–120	61.8
C	55.4	22–78	31.8

Mean reading performance in words per minutes (w.p.m.) and ranges in a group of normal subjects (N; n = 25), and in patients with calcarine damage (A; n = 8), additional partial involvement of the occipital white matter (B; n = 22) and additional extensive damage to the occipital white matter and, in part, to the ipsilateral posterior thalamus (C; n = 20). Performance values are taken at time of first testing. For the calculation of the severity of reading impairment (percentage performance), reading performance of normal subjects was set at 100%.

haemorrhage or stroke may be associated with reduction in cortical perfusion. These 'remote' effects can be interpreted in terms of interruption of fibre systems and deactivation of cortical areas interconnected with the lesioned subcortical structures (Perani *et al.*, 1987; Bogousslavsky *et al.*, 1988). It appears important, therefore, to differentiate primary lesion sites and remote effects in interpreting behavioural deficits, and in modelling the functional organization of the processes underlying complex behaviour. As far as occipital damage after posterior cerebral artery infarction is concerned, damage to the optic radiation, the calcarine cortex and the occipital white matter appears the most likely causal effect.

The hypothesis that damage to the posterior thalamus, and its reciprocal cortical connections, may impair oculomotor compensation of homonymous field loss, is supported by the known anatomical connections between this thalamic nucleus and cortical regions in the occipital, parietal and frontal lobes, and the limbic neocortex (for a review, *see* Robinson and Petersen, 1992). These structures are assumed to be part of a cortical–subcortical network subserving directed visual attention (Mesulam, 1981; Heilman *et al.*, 1985; Selemon and Goldman-Rakic, 1988; Corbetta *et al.*, 1993). Furthermore, fibre pathways connecting occipital, parietal and temporal cortical areas, coursing in the occipital white matter (e.g. Rockland and Pandya, 1981; Seltzer and Pandya, 1984; Morel and Bullier, 1990), might also have been damaged in our patients, thereby interrupting functional connections between these areas. In addition, projections from the striate and extrastriate cortex, occupying a large territory within the pontine nuclei (Glickstein *et al.*, 1990), and most likely associated with the guidance of saccadic eye movements, may also be affected by damage to the occipital white matter. Clinical observations support this view, although the picture is not very consistent. Motomura *et al.* (1986)

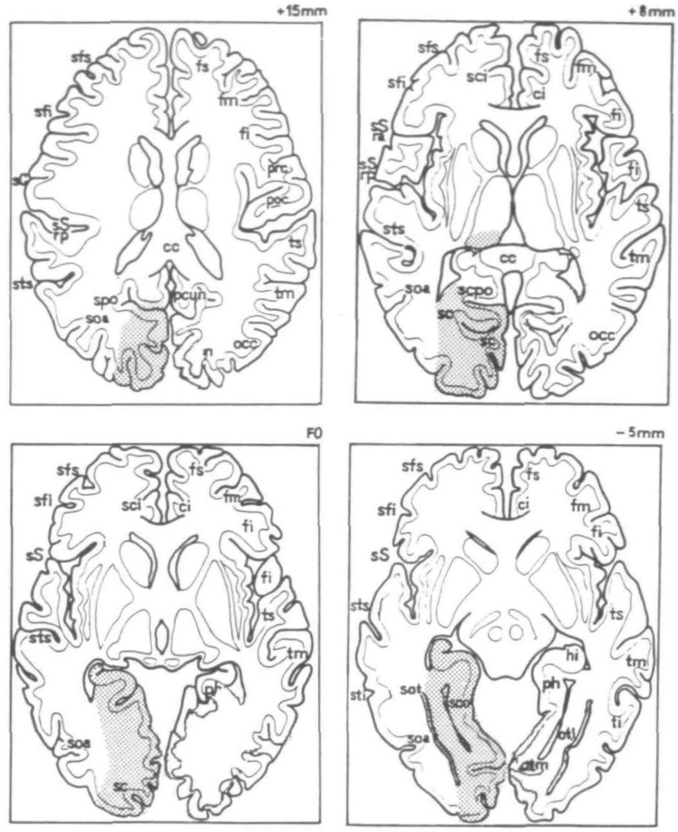

Fig. 13 Diagrams derived from axial MRI scans of a 46-year-old male patient with RH- hemianopia after left posterior artery infarction, which also affected the major portion of the occipital white matter and the posterior thalamus (grey areas). Slices are shown at FO-level, and at parallel sections at +15 mm, +8 mm and –5 mm. Visual field sparing was 2°; time since stroke was 14 weeks. Reading performance before systematic practice was 32 w.p.m., after 32 training sessions it was 44 w.p.m.. For abbreviations, *see* Fig. 12 legend.

Fig. 12 Diagrams derived from axial CT/MRI scans of patients with posterior artery infarctions mainly restricted to the calcarine cortex (**A** and **B**) or partly affecting the occipital white matter also (**C** and **D**). Lesion areas are shown in grey. Slices are shown at the level of the fronto-occipital line (FO) and parallel to this reference at +8 mm and +15 mm (*see* indications at the right top of single slices). **A**, A 50-year-old female patient, with right-sided hemianopia and 2° of field sparing; time since lesion = 8 weeks; reading performance = 120 w.p.m. **B**, A 46-year-old female patient, with left-sided hemianopia and 2° of field sparing; time since lesion: 7 weeks; reading performance: 105 w.p.m. **C**, A 46-year-old male patient, with right-sided hemianopia and field sparing of 2°; time since lesion: 9 weeks; reading performance = 82 w.p.m. **D**, A 52-year-old male patient, with left-sided hemianopia and field sparing of 2°; time since lesion = 8 weeks; reading performance = 87 w.p.m. Templates are taken from Hebel and von Cramon (1987). cc = corpus callosum; sts = sulcus (s.) temporalis superior; spo = s. parieto-occipitalis; soa = s. occipitalis anterior; scpo = s. calcarino-parieto-occipitalis ('common stem'); sc = s. calcarinus; sti = s. temporalis inferior; sot = s. occipito-temporalis; sco = s. collateralis;
pcun = praecuneus; cun = cuneus; occ = gyri occipitales (laterales); tm = gyrus (g.) temporalis medius; otm = g. occipito-temporalis medialis (lingual gyrus); otl = g. occipito-temporalis lateralis (fusiform gyrus); ti = g. temporalis inferior; ph = g. parahippocampalis; hi = hippocampus.

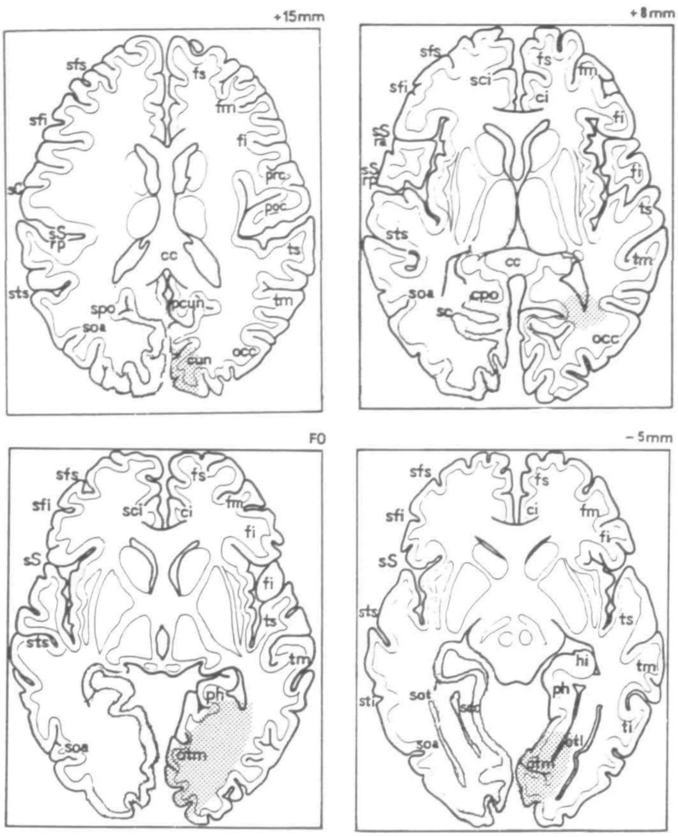

Fig. 14 Diagrams derived from axial CT scans of a 58-year-old male patient with left-sided hemianopia after left posterior artery infarction, which also affected the major portion of the occipital white matter (grey areas). Slices are shown at FO-level, and at parallel sections at +15 mm, +8 mm and –5 mm. Visual field sparing was 2°; time since stroke was 9 weeks. Reading performance before systematic practice with reading was 68 w.p.m., after 23 training sessions it was 106 w.p.m. For abbreviations, *see* Fig. 12 legend.

found that extensive damage beyond the posteromedial portion of the thalamus, involving nearby structures, are requisite for persistent contralateral visual neglect, as revealed by line bisection, line cancellation, drawing from memory and copying. Restricted right thalamus haemorrhage caused only transient unilateral visual neglect. Interestingly, no patient with left-sided thalamic haemorrhage (n = 13) showed signs of contralateral visual neglect. Reading was, unfortunately, not tested, and no information is available concerning the frequency of hemianopia in cases with left-sided thalamic damage. Ogren *et al.* (1984) reported unilateral deficiences during oculomotor search and scanning performance following a left pulvinar haemorrhage and surgical resection. Their patient demonstrated a marked difficulty in reading which could not be explained as alexia. Quantitative perimetry was not carried out but no evidence of a gross visual field defect to confrontation was found. The patient described by Henderson *et al.* (1982) suffered infarction of the right occipital lobe and the right thalamus. This patient exhibited 'pure alexia', dense left-sided hemianopia, impairments in visuo-spatial perception, including left-sided omissions in copying and drawing, cancellation and line bisection, and constructional disturbances. The authors regarded the alexia in this case to be mimicked by the visuo-spatial impairments; they did not, however, consider the parafoveal left-sided field loss as one possible factor. Henderson *et al.* (1982) concluded that a small right-sided occipital infarction, combined with damage to the adjacent white matter, and additional infarction of the ipsilateral (anterior) thalamus, may have been crucial in producing the severe visuo-spatial deficits in their patient. Damage restricted to the posterior thalamus was not found to impair reading in another patient, despite the presence of contralateral inattention under certain conditions of double simultaneous stimulation (Zihl and von Cramon, 1979). In contrast to the cases reported above, none of our patients showed signs of unilateral visual neglect at the time of testing, and reading impairment was not limited to patients with left-sided parafoveal field loss. Damage to the striate cortex and the occipital white matter, comprising subcortical-cortical reciprocal connections, may not cause persistent visual neglect but may impair, to varying degrees, oculomotor compensation of the parafoveal field loss. The lack of successful oculomotor compensation should, therefore, not be called visual neglect simply because patients either omit single targets or show, as a rule, a laborious, time-consuming strategy to explore the affected hemispace (Tegnér, 1994; Zihl, 1995). In the case of preservation of the thalamo-cortical fibre connections and the occipital white matter, visual information can be forwarded onto cortical areas and, via backward connections, saccades can be guided into the affected hemifield. In contrast, damage to the posterior thalamus or to the fibre systems interconnecting them with cortical areas may impair, or even prevent, oculomotor compensation because of the loss or reduction of both bottom-up and top-down influences. Systematic practice may, however, support the resumption of oculomotor activities closely related to, in our example, reading.

In conclusion, damage to the postgeniculate visual pathway and de-afferentation of visual cortical areas, but also of parietal and frontal cortical mechanisms involved in the spatial guidance of visual attention and associated eye movements, appears a reasonable explanation for the combination of parafoveal field loss and impaired shifting of attention and guidance of reading and exploratory eye movements. The high frequency of the combined striate cortex–white matter lesions after occipital damage, which leads to parafoveal field loss and reading impairment, may justify further use of the term 'hemianopic dyslexia' to characterize this special type of reading impairment. Furthermore, the visual field should no longer be regarded as just a sensory surface for the reception of visual stimuli, but as Williams and Gassel (1962) suggested, 'as much a measure of the attention as of the anatomical substrate', with 'some level of coherence of attention in the visual field'.

Acknowledgements

We wish to thank Ch. Schmid for assistance with the recordings and analysis of eye movements and treatment of patients, Dr P. Zahn for writing the software programs for the analysis and graphical presentation of the eye movement data, and Dr A. Yassouridis for help with the statistical analysis of the data.

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Received August 22, 1994. Revised January 18, 1995. Accepted March 17, 1995