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Rehabilitation of hemianopic dyslexia: are words necessary for re-learning oculomotor control?

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Unilateral homonymous visual field disorders after brain damage are frequently associated with a severe impairment of reading, called hemianopic dyslexia. A specific treatment method has been developed which allows patients to regain sufficient reading performance by re-learning eye-movement control in reading through systematic oculomotor practice. However, it is still unclear whether the treatment effect associated with this training procedure critically depends on using text material. We therefore evaluated the effectiveness of systematic oculomotor training with non-text material (Arabic digits) in comparison with conventional oculomotor training using text material (words) in 40 patients with unilateral homonymous visual field disorders and hemianopic dyslexia. Non-text training was found to be as effective as conventional text training in improving reading performance and associated eye-movements in these patients. Our results suggest that using words is not critical to the treatment effect of this training procedure. Thus, lexical-semantic processes seem not to be necessary for re-learning eye-movement control in hemianopic dyslexia.

Keywords: hemianopia; reading; eye-movements; oculomotor control; perceptual learning

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Introduction

Unilateral homonymous visual field disorders are common functional impairments after acquired injury to the post-chiasmatic visual pathway. Sufficient spontaneous recovery of the visual field occurs rarely (Zihl and Kennard, 1996; Zhang *et al*., 2006), and most patients show severe impairments of reading (80%) and visual exploration (60%) (Zihl, 2000, 2003). Mauthner (1881) was the first to describe the acquired reading disorder in which patients with unilateral homonymous visual field disorders have severe reading difficulties despite intact language functions. Wilbrand (1907) termed it 'macular-*hemianopic* reading disorder' (Poppelreuter, 1917/1990) since hemianopia is the most frequent visual field disorder, followed by quadranopia and paracentral scotoma (Zihl, 2000).

In hemianopic dyslexia, the visual bottom-up and attentional top-down control of text processing and eye-movements involved in reading is disturbed (for a comprehensive review, see Schuett *et al*., 2008). Consequent impairments of word identification and the ability to plan and guide reading eye-movements become manifest as pronounced slowness of reading, visual omission and guessing errors as well as a severely disorganized oculomotor scan-pattern in reading—the cardinal symptoms of hemianopic dyslexia (Mackensen, 1962; Gassel and Williams, 1963; Eber *et al*., 1987; Schoepf and Zangemeister, 1993; Zihl, 1995*a*, 2000; De Luca *et al*., 1996; Trauzettel-Klosinski and Brendler, 1998; Leff *et al*., 2000; McDonald *et al*., 2006; Spitzyna *et al*., 2007). Hemianopic dyslexia represents a substantial impediment to patients' vocational, educational and daily-life activities and counts as an important cerebral visual impairment (Zihl, 2000; Papageorgiou *et al*., 2007).

Although spontaneous oculomotor adaptation to visual field loss in visual exploration is more likely (40%) than patients compensating for their reading impairment (20%) (Zihl, 2000), the majority of neuropsychological rehabilitation studies on visual field disorders has focused on the visual exploration impairment (for a systematic review, see Bouwmeester *et al*., 2007). To date, only five studies have dealt with the rehabilitation of hemianopic dyslexia (Zihl *et al*., 1984; Kerkhoff *et al*., 1992; Zihl, 1995*a*, 2000; Spitzyna *et al*., 2007). The first systematic attempt to improve reading in patients with visual field loss dates back to Poppelreuter (1917/1990). He developed a special reading training for addressing the 'disturbance of the co-ordination of the reading gaze-shifts' (p. 224) he observed in his patients. Poppelreuter showed convincingly that by systematic practice of oculomotor control 'relearning of reading was successful' (p. 249).

Poppelreuter's treatment rationale led to the development of a compensatory oculomotor treatment method for hemianopic dyslexia (Zihl *et al*., 1984), which proved its effectiveness in a number of investigations (Kerkhoff *et al*., 1992; Zihl, 1995*a*, 2000; Spitzyna *et al*., 2007). It involves supervised, systematic practice of reading eye-movements with text material (words) to overcome the effects of parafoveal visual field loss in reading. Patients learn to efficiently use saccadic eye-movements to bring the entire word from the blind into the seeing hemifield for identification. As a consequence, patients regain sufficient reading performance with long-term stability, confirming the importance of effective oculomotor control in reading. Treatment effects are characterized by an increase in reading speed and accuracy, and the re-establishment of a systematic oculomotor scan-pattern in reading. These effects were attributed to training-related oculomotor adaptation to parafoveal visual field loss in reading (Zihl, 1995*a*, 2000).

Thus far only text material, either moving (Zihl, 1984, 1995*a*, 2000; Kerkhoff *et al*., 1992; Spitzyna *et al*., 2007) or static (Zihl, 2000), has been used in this treatment procedure. However, it is still unclear whether the treatment effect associated with this treatment procedure for hemianopic dyslexia critically depends on using text material (words). We therefore investigated whether words and thus lexical-semantic processes are necessary for re-learning reading eye-movement control in parafoveal visual field loss, or whether non-text material lacking lexical-level linguistic information (Arabic digits) is sufficient. This study evaluated the effectiveness of oculomotor training using time-limited presentation of static non-text material in comparison with conventional oculomotor training with static text material (Zihl, 2000). In addition to assessing the treatment effects on reading performance and associated eye-movements in patients with hemianopic dyslexia, we investigated whether these effects are specific to reading or whether there is a transfer of training-related improvement to visual exploration performance.

Investigating the therapeutic potential of non-text training is also an attempt to improve current rehabilitative efforts. Clinical observations suggest that patients with hemianopic dyslexia seem to over-rely on linguistic processes when attempting to identify words. Their common yet maladaptive strategy is to elaborate the meaning of an incompletely perceived word by guessing rather than first inspecting the entire word. Lexical-semantic processing comes into play too early, which disrupts further acquisition of text information located in the blind hemifield and interferes with the treatment goal, i.e. that patients learn to visually apprehend before comprehending text (Zihl, 2000). Avoiding text material in the treatment of hemianopic dyslexia may eliminate not only such undesired linguistic top-down interference but also the additional cognitive load associated with word processing itself (McCann *et al*., 2000; Shaywitz *et al*., 2001; Lien *et al*., 2008). Reading-related oculomotor training with non-text material may therefore be less effortful for the patient.

Methods

Subjects

Forty patients with left- ($n = 16$) or right-sided ($n = 24$) homonymous parafoveal visual field loss and hemianopic dyslexia participated in this study. Homonymous hemianopia was the most frequent cause of parafoveal visual field loss; 12 patients had a left-sided, 12 a right-sided hemianopia. Six patients had a right-sided upper and two a right-sided lower quadranopia. Six patients had a right-sided, two a left-sided paracentral scotoma. The parafoveal visual field was compromised in all patients. Mean visual field sparing, i.e. the extent of visual field in degrees between the fovea and the visual field border along the left or right horizontal axes, was 2.1° (range: 1–4°). In all patients, aetiology of brain injury, as verified by cranial CT and/or MRI, was an infarction (82.5%) or haemorrhage (17.5%) in the territory of the posterior cerebral artery causing a lesion to the occipital cortex. Time between the occurrence of brain injury and initial assessment was on average 30 weeks (range: 5–220). None of the patients had received any treatment for their visual field defect. Patients showed no evidence of associated cerebral visual disorders, including reduced visual acuity (<0.90 for near and far binocular vision), impaired spatial contrast sensitivity (Vistech contrast sensitivity test, 1988), visual adaptation, disturbances of the anterior visual pathways or of the oculomotor system, macular disease (according to ophthalmologic examination), nor aphasia, premorbid reading disorders, pure alexia (vertical word reading test; Zihl, 1995*a*), impairments of visual-lexical numerical processing (horizontal and vertical number reading; Zihl, 1995*a*) or verbal memory deficits [WMS-R (Logical Memory I/II); Wechsler, 1987]. None of the patients had visual neglect as assessed by tests in accordance with the Behavioural Inattention Test, composed of line bisection, letter and star cancellation, figure and shape copying and drawing from memory (see Halligan *et al*., 1991). All patients were native German speakers and had at least 5 years of education.

All patients complained of moderate to severe difficulties in reading and showed impaired reading performance. Patients were therefore systematically treated to compensate better for their parafoveal visual field loss in reading. Half of patients received treatment with text material (text training, Group A, $n = 20$), the other half was treated with non-text material (non-text training, Group B, $n = 20$). For treatment allocation, we used age, type, side and severity (i.e. visual field sparing) of visual field loss as stratifying variables before testing was carried out. Before treatment, there were no differences between both groups either for demographic and clinical variables or for reading and visual exploration performance (Table 1). Mean near Snellen visual acuity was 0.97 (SD: 0.05, range: 0.9–1.0) in Group A, and 0.98 (SD: 0.04, range: 0.9–1.0) in Group B. We used a single subject baseline design with a treatment-free interval before and after oculomotor training with text or non-text material wherein every patient served as his or her own control. Visual fields and reading performance were assessed at four time-points, i.e. at initial assessment (T1), before (T2) and after (T3) treatment, and after a follow-up interval (T4). Time intervals between assessments did not differ between

Table 1 Demographic and clinical details and behavioural measurements for both treatment groups [mean (SD, range)]

	Text training (Group A: $n = 20$)	Non-text training (Group B: $n = 20$)	*P*-value
Age (years)	58.8 (11.8, 28–80)	58.7 (13.8, 23–83)	0.980
Sex			
Female	3 (15%)	3 (15%)	
Male	17 (85%)	17 (85%)	
Education (years)	9.7 (3.2, 5–18)	10.0 (4.1, 5–19)	0.989+
Time since lesion (weeks)	28.9 (28.4, 5–97)	31.0 (47.0, 5–220)	0.839+
Aetiology			
Posterior infarction	18 (90%)	15 (75%)	
Occipital haemorrhage	2 (10%)	5 (25%)	
Type of visual field loss			
Hemianopia	12 (60%)	12 (60%)	
Upper quadranopia	3 (15%)	3 (15%)	
Lower quadranopia	1 (5%)	1 (5%)	
Paracentral scotoma	4 (20%)	4 (20%)	
Side of visual field loss			
Left	8 (40%)	8 (40%)	
Right	12 (60%)	12 (60%)	
Visual field sparing (°) (pre-treatment)	1.9 (0.9, 1–4)	2.2 (1.0, 1–4)	0.562
Reading speed (w.p.m.) (pre-treatment)	92.8 (40.7, 33–162)	100.9 (27.2, 50–148)	0.464
Visual exploration time (s) (pre-treatment)	31.8 (14.6, 14–65)	34.5 (13.9, 15–72)	0.315
Interval T1–T2 (weeks)	6.0 (3.5, 2–15)	4.6 (3.0, 1–13)	0.155+
Interval T2–T3 (number of training sessions within 2 weeks)	10.5 (2.0, 7–14)	9.6 (2.0, 6–12)	0.141
Interval T3 – T4 (weeks)	10.9 (2.6, 6–15)	11.4 (2.7, 7–16)	0.518

Statistical comparisons were made between treatment groups. *P*-values for two-tailed independent *t*-tests or +Mann–Whitney-U-tests (where normality assumptions were violated as assessed by Shapiro–Wilk tests) are given.

groups (Table 1). In addition, we assessed visual exploration performance and obtained subjective reports (T2, T3). In a representative sub-sample of seven patients for each treatment group, we recorded eye-movements during reading (T2, T3, T4) and visual exploration (T2, T3). All patients gave informed consent to participate in this study.

Visual field testing

Monocular and binocular visual fields were measured using kinetic perimetry with a standard Tübingen perimeter (Aulhorn and Harms, 1972). Target diameter was 1.2°, 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 perimeter's centre. Patients were instructed to fixate a small red spot of light (diameter: 0.5°) in the centre of the sphere and to press a response button as soon as they detected the target. Fixation accuracy was monitored through a telescope. The visual field border was determined along 16 meridians. Perimetric resolution was 0.5° and measurement error was 0.5° within the central 15° of the visual field, which is relevant for reading.

Assessment of reading and visual exploration performance; subjective reports

Reading performance was assessed by using four parallel versions of a standardized reading test shown to be sensitive to changes in reading performance during treatment (Zihl, 1995*a*, 2000). Each text consisted of 200 words (in 14pt Arial font) arranged in 20 double spaced, left-aligned lines printed on a white sheet of paper. The texts were characterized by short sentences and simple syntactic structure and were standardized for content [taken from Gotthold E. Lessing's animal fables (in German)]. The frequency of each word length (in number of characters) was the same for each text. Patients were instructed to read the text aloud as accurately and quickly as possible. Reading time and errors were recorded. Reading performance was defined as number of words correctly read per minute (w.p.m.); this measure incorporates both (oral) reading speed and accuracy. The number of reading errors is therefore not reported in the results section. Normative data were available from a sample of 80 control participants [40 females, 40 males; mean age: 41.3 years (SD: 13.4)]. Average corrected reading speed was 161.1 w.p.m. (SD: 21.3, range: 121–218).

For assessing visual exploration performance stimulus patterns consisting of simple forms have proven to be a valuable test, which is sensitive to changes in visual exploration performance during treatment (Zihl, 2000). We used a cancellation task with 20 black diamonds (targets) randomly embedded in 22 black dots and crosses (distractors) on a sheet of white paper. At a viewing distance of 30 cm the stimulus array subtended 44.6° horizontally and 35° vertically; stimulus diameter was 0.8°. Patients were asked to mark all diamonds with a pencil as quickly as possible with their right hand. No instruction was given on how to proceed and patients were not informed about the number of targets. Visual exploration performance was defined as the time required to perform the task. Since all patients performed the task errorless, errors are not reported in the results section. Normative data were available from 25 control participants [12 females, 13 males; mean age: 38.0 years (SD: 10.7)], who required on average 13.2 s (SD: 1.3, range: 9.1–17.2) to perform this task errorless.

The reading and visual exploration tests were administered under normal daylight conditions. The experimenter sat to the right of the patient and centred the test sheets to the patient's body axis at a distance of 30 cm. Eye and head movements were not restricted. In addition we obtained informal subjective reports on reading and visual exploration performance by using the corresponding questions of a validated questionnaire (Kerkhoff *et al*., 1990). In addition, we observed patients during training sessions and collected their subjective impressions of the training method (subjective rehabilitation experience); after treatment, we also asked patients whether they were satisfied with the treatment outcome.

Recording of eye-movements in text reading and visual exploration

In a sub-sample of 14 patients, we obtained oculomotor measures for silent reading [T2, T3 and T4 (except for one patient)] and visual exploration (T2, T3). Eye-movements were recorded using a video-based, infrared remote eye tracking system (iView X RED, SensoMotoric Instruments GmbH, Teltow, Germany). Viewing was binocular and the position of the dominant eye was sampled at 50 Hz, with a spatial resolution of 0.1°. Prior to the recording session of each patient, the equipment was calibrated using a 9-point grid. During the registration of eye-movements, patients sat in front of a screen which subtended 40° horizontally and 32° vertically, with the head fixed at a distance of 140 cm. Room illumination was very low (1 lux) to avoid cues from the surroundings.

Materials for recording eye-movements during silent text reading consisted of three parallel versions of a standardized reading test shown to be sensitive to changes in oculomotor reading measures during treatment (Zihl, 1995*a*, 2000). Each text consisted of 61 words arranged in nine, left-aligned lines. Letter size was 1.0°, allowing for the maximum reading rate (Legge *et al*., 1985); letter width subtended 0.5°; spacing between letters was 0.2° and 1° between words. Single lines were separated vertically by 2°. Luminance of the black letters was 0.2 cd/m^2 and that of the white background was 27 cd/m^2. The texts were characterized by short sentences and simple syntactic structure and were also standardized for content. Patients were asked to read the text silently and only once, with no further instructions on how to proceed. For testing comprehension and to provide evidence that patients actually read the texts, they were also asked to reiterate its content after reading the text, which all patients did correctly. Eye-movement recording was started at the onset of text presentation and was ended after the patient indicated completion of reading. At each time-point (T2, T3, T4), one text was presented. Normative data were available from a sample of 25 control participants [12 females, 13 males; mean age: 38.0 years (SD: 10.7)].

For eye-movement recording during visual exploration, irregular stimulus patterns consisting of 20 white dots (diameter: 0.9°) on a black screen were used, which have been found to be sensitive to changes in oculomotor visual exploration measures during treatment (Zihl, 1995*b*, 1999, 2000). Dot luminance was 27 cd/m^2; background luminance was 0.2 cd/m^2. The minimal spatial separation of any pair of adjacent dots was 7° (maximum distance: 10.5°). Patients were asked to silently count the dots presented on a screen; no instruction was given on the number of dots or how to proceed with counting or searching. This test is similar to the dot cancellation test (Lezak *et al*., 2004) but did not include feedback on which dots have already been processed. Eye-movement recording in the visual exploration condition was started with the onset of dot pattern presentation and was ended when the patient indicated to have counted all dots. At the end of recording, each patient was asked to report the number of dots. Since all patients reported the 20 dots correctly, errors are not reported in the results section. One trial was carried out at each time-point (T2, T3). Normative data were available from 30 control participants [15 females, 15 males; mean age: 51.6 years (SD: 10.1)].

For each participant, 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 fixation duration was set at 100 ms. Recordings with >15% loss of eye-movement data (due to lid closures or saccadic eye shifts to positions outside the registration area) were not included in the analysis. We analysed the following global temporal and spatial oculomotor measures for the assessment of reading eye-movements: Mean number and duration (ms) of fixations, percentage of fixation repetitions (fixations at previously fixated points, i.e. regressions), number of forward saccades, mean amplitude of all saccades (°) and scanpath length (i.e. the sum of saccadic amplitudes (°) between the appearance of the text and the verbal report by the patients that reading had been completed). For assessing oculomotor visual exploration performance, we analysed the mean number and duration (ms) of fixations, percentage of fixation repetitions and the mean amplitude (°) of all saccades.

Method of treatment: reading training with text and non-text material

The treatment was performed using the software-based training program as developed by Zihl (2000, pp. 81–89). Text and non-text training material was presented in the centre of a 17-in. high-resolution monitor. Letter and digit size was 2°, and width subtended 1°; spacing between letters (text material) was 0.4°. We used yellow for the training material and a dark blue for the background. These size and colour specifications have shown to allow for comfortable reading and oculomotor practice (Zihl, 2000). Room illumination was low (<5 lux) in order to minimize the effects of glare from the monitor. Patients were seated in front of the screen, at a distance of 50 cm. The treatment was administered and supervised by the experimenter, who sat beside the patient to give verbal feedback on reading errors during training (supervised learning). Reading errors were always immediately corrected by the experimenter after each trial. In addition, the experimenter monitored that patients did not resort to the common strategy of guessing only half-seen words instead of first using eye-movements to perceive words as a whole. Moreover, she monitored that patients did not use head- instead of eye-movements, another maladaptive strategy patients often resort to. Preventing such maladaptations is of great importance in the rehabilitation of visual field disorders since they increase functional visual impairment, interfere with the acquisition of an adaptive oculomotor strategy and delay treatment progress (Zihl, 2000).

Text training (Group A)

Single words of different lengths, ranging from 3 to 12 letters, were used as training material for Group A. Each training trial was composed of the time-limited presentation of one single word in the centre of the screen. Patients were instructed to perceive each word as a whole before reading it aloud by intentionally shifting their gaze, as quickly as possible, from the screen's centre to the beginning (in cases with left-sided visual field loss) or to the end (in cases with right-sided visual field loss) of each word. This paradigm allows reading-related eye-movements to be trained and reinforced by the patient's normal internal visual feedback and feedback given by the experimenter. During the course of training, the length of the presented words was systematically increased from 3- to 13-letter-words. When a patient was able to read at least 90% of the words of a given length correctly, presentation time was reduced from ~1000 to eventually 300–400 ms. The final training stage involved the randomized presentation of words of different lengths. By adopting this procedure, patients were forced to make quicker and more efficient saccades in order to perceive and read the whole word before its disappearance. In addition, patients learned to flexibly adjust the size of saccades according to word length. This training protocol was adjusted to individual reading performance and training progress. Training was completed when patients reached a defined criterion (at least 90% correct responses) for any level of difficulty used. An individual training session lasted ~45 min; it consisted of 10 practice units (30 trials each) and short or, if required, longer breaks between units. Patients required on average 11 training sessions, which were carried out within 2 weeks for each patient (interval T2–T3; Table 1).

Non-text training (Group B)

Non-text training required saccadic eye-movements that are arguably similar to those made during text training but did not involve lexical-semantic linguistic processing. In the design of our non-text training material special care was taken to preserve the main visual feature of a word that is critical for inducing reading saccades, i.e. word length (Ducrot and Pynte, 2002; Inhoff *et al.*, 2003). We created word-like units that are variable in length and comprise of a beginning and end, which can therefore be expected to support similar saccadic activity as real words. For excluding lexical-level linguistic information and thus lexical-semantic processes we created 'digit-words' consisting of Arabic digits. Arabic digits do not contain any semantic information (Dehaene and Cohen, 1995; Dehaene *et al.*, 2004). Each digit word consisted of two Arabic digits, i.e. a 'beginning'-digit (1–9) and an 'end'-digit (0–9). Different stimulus lengths were created by varying the space between the two digits; the spatial extent of a 12-'letter'-digit-word, for an example, resembles the average spatial extent of a 12-letter word. The second type of digit-words contains an additional digit which is inserted at random positions between the beginning- and end-digit. For each length (3- to 12-'letter'-widths), we created a different digit-word selection out of 90 possible beginning- and end-digit combinations; yet, adjacent digits were never identical. Each training trial was composed of the time-limited presentation of a single digit-word in the centre of the screen. Patients were instructed to intentionally shift their gaze, as quickly as possible, to the 'beginning', i.e. left, digit (in cases with left-sided visual field loss) or to the 'end', i.e. right, digit (in cases with right-sided visual field loss) of each digit-word before reading the two (or three) digits aloud sequentially (e.g. digit-word '2 8 3' is to be read as '2, 8, 3'). The training was carried out exactly according to the same training protocol and procedure as in Group A, with only the training material being exchanged. Patients required on average 10 training sessions, which were carried out within 2 weeks for each patient (interval T2–T3; Table 1).

Data analysis

For testing the treatment effects of text and non-text training, we performed a repeated measures analysis of variance with time as within-subject factor for each group (within-group effects) and the same analysis with treatment group as between-subject factor (between-group effects). Where sphericity assumptions were violated as assessed by Mauchly's W-test, we applied the Greenhouse-Geisser correction to the degrees of freedom. *Post hoc* paired comparisons between time-points were performed using two-tailed related samples *t*-tests. Comparisons between treatment groups were performed using two-tailed independent sample *t*-tests. As multiple tests were carried out, the significance level was adjusted using a Bonferroni correction to an alpha-level of 0.05 for multiple comparisons.

Results

Reading and visual exploration before treatment

Before treatment, all patients in both treatment groups complained of difficulties in reading and visual exploration. Patients reported that reading had become an extremely laborious and fatiguing activity. They described reading as being very slow and reported missing syllables and words as well as difficulties in finding the beginning of a new line (especially in left-sided visual field loss) and in moving the eyes smoothly along a line of text (especially in right-sided visual field loss). In addition, patients complained about colliding with obstacles, missing objects or persons located in the blind field and losing orientation especially in unfamiliar surroundings. These reports were in close agreement with patients' objective test results as well as corresponding eye-movement recordings and were similar in both groups. All patients showed impaired reading and visual exploration performance and severely altered eye-movement patterns.

Reading performance

Before treatment, corrected reading speed was considerably reduced in all patients of both treatment groups (Table 2, T2); there were no differences between groups for reading speed (Table 1). The reading errors of patients consisted mainly of visual omissions of pre- or suffixes and small words or guessing errors, i.e. meaningful completion of only partially seen words.

Yet, the individual reading speeds of 12 patients were classed as unimpaired in that they fell within 2 SD of the average performance of control participants [A ($n = 7$): 140.1 w.p.m. (SD: 11.2, range: 127–162); B ($n = 5$): 133.4 w.p.m. (SD: 11.4, range: 120–148)]. However, these patients, nevertheless, complained of a reading impairment, especially when comparing reading performance with their premorbid performance as very skilled and avid readers. After treatment, they also showed a significant improvement in reading performance, which they were satisfied with. Their mean reading speed increased to 166.3 w.p.m. (SD: 10.7, range: 156–187) in Group A ($n = 7$) and to 160.2 w.p.m. (SD: 12.0,

Table 2 Reading performance and related oculomotor measures before (T2) and after treatment (T3) and at follow-up (T4) [mean (SD), [range]]

	Text training (Group A: $n = 20$):			Non-text training (Group B: $n = 20$)			N
	T2	T3	T4	T2	T3	T4	
Reading speed (w.p.m.)	92.8 (40.7) [33–162]	127.8 (36.8) [64–187]	134.1 (35.3) [69–189]	100.9 (27.2) [50–148]	136.6 (27.7) [79–179]	142.5 (27.8) [82–183]	161.1 (21.3)
Number of fixations	105.3 (18.1) [83–135]	66.6 (18.5) [50–97]	62.8 (18.8) [46–89]	76.7 (14.0) [59–93]	51.6 (12.9) [33–71]	46.7 (11.3) [34–63]	56.0 (11.0)
Fixation repetitions (%)	26.3 (7.6) [16.3–37.5]	18.5 (6.4) [10.7–28.6]	15.1 (5.8) [8.7–22.6]	23.9 (12.9) [10.1–40.9]	14.0 (11.5) [4.2–35.7]	9.0 (7.8) [3.2–23.5]	15.2 (9.6)
Fixation duration (ms)	360.0 (108.2) [240–510]	274.3 (50.0) [220–360]	266.7 (38.3) [230–320]	340.0 (84.7) [260–460]	232.9 (47.2) [160–300]	233.3 (31.4) [190–280]	250.0 (20.0)
Number of forward saccades	68.6 (28.4) [45–121]	45.9 (23.7) [27–88]	43.5 (20.2) [25–74]	53.6 (16.5) [25–72]	40.7 (11.9) [24–60]	37.7 (11.4) [22–52]	41.0 (8.0)
Saccadic amplitude (°)	3.5 (1.0) [2.5–5.4]	4.7 (1.3) [2.9–6.7]	4.6 (1.4) [3.1–6.6]	3.7 (0.8) [2.8–5.2]	4.3 (1.2) [3.0–6.8]	4.5 (1.1) [3.4–6.5]	4.3 (0.7)
Scanpath length (°)	540.8 (87.3) [432.9–698.4]	445.1 (110.9) [321.9–608.1]	408.9 (88.9) [322.4–525.6]	528.4 (172.6) [334.7–809.9]	409.5 (107.2) [287.3–619.7]	362.0 (59.9) [278.3–431.2]	358.4 (74.2)

Normative data from control samples are given for comparison (N).

Table 3 Visual exploration performance and related oculomotor measures before (T2) and after treatment (T3) [mean (SD), (range)]

	Text training (Group A: $n = 20$)		Non-text training (Group B: $n = 20$)		N
	T2	T3	T2	T3	
Time (s)	31.8 (14.6) [14–65]	30.7 (14.0) [12–59]	34.5 (13.9) [15–72]	34.2 (13.6) [14–69]	13.2 (1.3)
Number of fixations	50.4 (10.4) [32–59]	49.1 (11.6) [27–58]	47.3 (7.0) [39–58]	44.9 (6.2) [38–53]	21.0 (4.0)
Fixation repetitions (%)	23.8 (8.8) [9.4–36.5]	23.8 (8.2) [14.6–35.4]	25.4 (9.6) [12.2–39.6]	25.8 (7.1) [15.8–34.0]	12.7 (6.2)
Fixation duration (ms)	300.0 (57.7) [200–400]	278.6 (27.9) [250–330]	314.3 (69.0) [200–400]	305.7 (48.3) [260–380]	270.0 (20.0)
Saccadic amplitude (°)	4.7 (0.4) [4.1–5.2]	5.0 (0.8) [4.0–6.5]	4.5 (0.7) [3.4–5.3]	4.4 (0.7) [3.3–5.2]	5.6 (0.7)

Normative data from control samples are given for comparison (N).

range: 148–179) in Group B ($n = 5$); their mean increase in reading speed was on average (A) 26.1 w.p.m. (SD: 9.3, range: 17–45) and (B) 26.8 w.p.m. (SD: 5.6, range: 18–32), respectively, and reached statistical significance [A: $t(6) = -7.42$, $P < 0.001$; B: $t(4) = -10.64$, $P < 0.001$].

Oculomotor reading measures

The reading eye-movement patterns (recorded in a representative sub-sample of seven patients for each treatment group) were characterized by an increased number of fixations, a higher percentage of fixation repetitions as well as prolonged fixation durations. Saccades were much smaller and patients made many more forward saccades. Length of reading scanpaths was markedly increased (Table 2, T2). There were no significant differences in these oculomotor measures between treatment groups [largest $t(12) = 1.59$, $P = 0.138$], except for number of fixations [$t(12) = 3.30$, $P = 0.006$].

Visual exploration performance

All patients in both treatment groups showed markedly elevated visual exploration times (Table 3, T2), and there were no significant differences between groups (Table 1). Although the individual visual exploration times of two patients (A: 1; B: 1) were classed as unimpaired in that they fell within 2 SD of the average performance of control participants, these patients nevertheless complained about colliding with objects and navigation difficulties.

Oculomotor visual exploration measures

The eye-movement patterns in visual exploration (recorded in a representative sub-sample of seven patients for each treatment group) were characterized by an increased number of fixations and a higher percentage of fixation repetitions. We also found a modest decrease in saccadic amplitude and fixation duration (Table 3, T2). There were no significant differences in these oculomotor measures between treatment groups [largest $t(12) = 0.77$, $P = 0.455$].

The effect of text and non-text training: within- and between-group analyses

All patients in both treatment groups reported an improvement in reading after training. Patients described reading to be much quicker, more fluent and less effortful than before training; they also reported that omitting syllables and words occurred only very rarely and reading became much more accurate. In addition, they reported to be more efficient in guiding eye-movements through the text and that comfortable reading time increased substantially. However, all patients still complained of the same difficulties in visual exploration that were reported before treatment. These subjective reports were in close agreement with the treatment effects as verified by objective test results and similar in both training groups: All patients showed an increase in reading speed and accuracy as well as more systematic reading eye-movement patterns whereas visual exploration performance and related eye-movement patterns remained impaired.

During training sessions, we observed that patients who practised eye-movements with text material often tried to guess the presented yet only half-seen word rather than following the instruction to first inspect each word by making an eye-movement, which is consistent with previous observations (Zihl, 2000); moreover, the reading task itself, i.e. processing, identifying and reading the presented words, often seemed to distress patients. Patients who practised eye-movements with non-text material less frequently reported to be distressed, tired or frustrated during training sessions than patients who received text training. When asked whether they were satisfied with the treatment outcome, all patients of both groups replied in the affirmative.

Reading performance

The results are illustrated in Fig. 1 (see also Table 2). Both, text and non-text training led to a significant improvement in reading performance (A: $n = 20$, B: $n = 20$), as indicated by a significant effect of time on corrected reading speed in both treatment groups [A: $F(1.0,19.9) = 73.49$, $P < 0.001$; B: $F(1.1,20.3) = 90.96$, $P < 0.001$]. Reading speed remained unchanged between initial and pre-treatment assessment [A: $t(19) = -1.72$, $P = 0.101$; B: $t(19) = -0.81$, $P = 0.426$]. After treatment, reading speed increased significantly [A: $t(19) = -7.62$, $P < 0.001$; B: $t(19) = -8.87$, $P < 0.001$]; in addition, patients did not show visual omission and guessing errors any longer. Although patients of both groups showed another very small yet significant increase after follow-up [A: +6.4 w.p.m. (SD: 3.6, range: 2–15), $t(19) = -7.92$, $P < 0.001$; B: +5.9 w.p.m. (SD: 3.7, range: 1–16), $t(19) = -7.12$, $P < 0.001$], the major improvement in reading performance was confined to the treatment interval (Table 4): the pre-post-treatment increase in reading speed was consistently and significantly larger than the very small increase after follow-up, which is also unlikely to reflect any meaningful difference in reading performance [A: $t(19) = 5.89$, $P < 0.001$; B: $t(19) = 6.79$, $P < 0.001$ (two-tailed related samples *t*-test)].

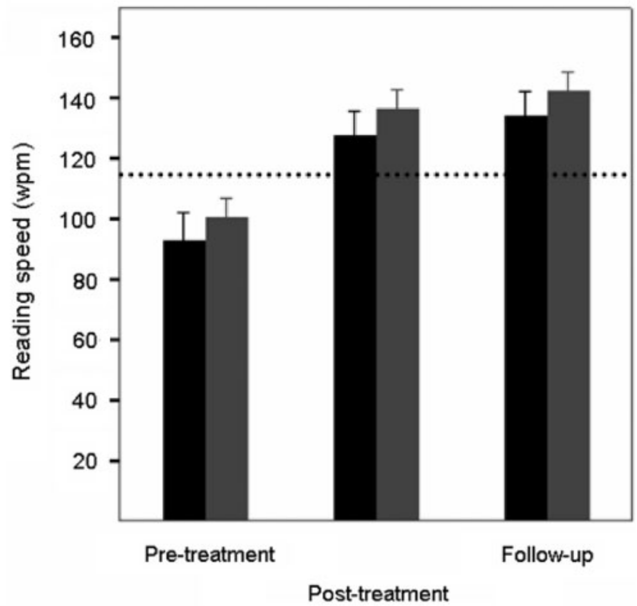

Fig. 1 Mean reading speed (w.p.m.) before and after treatment and at follow-up for both training groups (text training: black bars, non-text training: grey bars; vertical bars indicate 1 SE). Dotted line indicates cut-off value based on control sample ($n = 80$).

The individual reading speeds of eight patients in Group A [89.0 w.p.m. (SD: 16.8, range: 64–113)] and of six patients in Group B [101.2 w.p.m. (SD: 16.6, range: 79–118)] were still classed as impaired in that they fell below 2 SD of the average performance of control participants after treatment. However, these patients showed a significant improvement in reading performance [A ($n = 8$): +26.1 w.p.m. (SD: 9.0, range: 13–41), $t(7) = -8.24$, $P < 0.001$]; [B ($n = 6$): +22.7 w.p.m. (SD: 11.0, range: 13–38), $t(5) = -5.04$, $P = 0.004$] and reported to be satisfied with this outcome when compared with their pre-treatment performance [A: 62.9 w.p.m. (SD: 23.2, range: 33–96); B: 78.5 w.p.m. (SD: 21.4, range: 50–105)].

Between-group analyses ($n = 40$) revealed that these treatment effects of text and non-text training were the same (Table 4). We obtained a significant main effect of time across treatment groups [$F(1.06,40.1) = 162.73$, $P < 0.001$], and neither the effect of treatment group nor its interaction with time were significant [$F_{trgroup}$ $(1,38) = 0.87$, $P = 0.358$; $F_{int}(1.06,40.1) = 0.01$, $P = 0.938$]. Mean increases in reading speed did not differ between groups [$t(38) = -0.12$, $P = 0.903$].

Oculomotor reading measures

Likewise, both text and non-text training led to a significant improvement in reading eye-movements (recorded in seven patients for each treatment group), as reflected in

Table 4 The effects of text and non-text training on reading performance and related oculomotor measures during the treatment interval [mean (SD, range); magnitude of mean improvements are also given in percent]

	Text training (Group A: $n = 20$)	Non-text training (Group B: $n = 20$)
Increase in reading speed (w.p.m.)	+35.0 (20.5, 13–91) [+38%]	+35.7 (18.0, 13–82) [+35%]
Decrease in number of fixations	−38.7 (9.5, 25–48) [−37%]	−25.1 (8.1, 12–37) [−33%]
Decrease in fixation repetitions (%)	−7.8% (1.9, 5.3–10.4) [−30%]	−11.7% (8.6, 0–23.7) [−41%]
Decrease in fixation duration (ms)	−85.7 (66.3, 0–190.0) [−24%]	−107.1 (76.1, 0–210.0) [−31%]
Decrease in number of forward saccades	−22.7 (9.3, 9–36) [−33%]	−12.9 (8.7, 1–28) [−24%]
Increase in saccadic amplitude (°)	+1.2 (0.7, 0.4–2.3) [+34%]	+0.6 (0.6, 0.1–1.6) [+16%]
Decrease in scan path length (°)	−95.8 (62.1, 30.8–187.4) [−18%]	−118.9 (99.5, 36.1–294.0) [−23%]

a significant effect of time for all oculomotor reading measures in both groups [A: smallest $F(1.1,5.3) = 8.92$, $P = 0.028$; B: smallest $F(1.0,5.0) = 6.94$, $P = 0.046$]. The results are illustrated in Fig. 2 (see also Table 2). Pre- and post-treatment comparisons revealed a significant decrease in number of fixations, percentage of fixation repetitions, fixation duration, number of forward saccades and scanpath length as well as a significant increase in saccadic amplitude [A: smallest $t(6) = 3.42$, $P = 0.014$; B: smallest $t(6) = -2.67$, $P = 0.037$]. After follow-up, all oculomotor measures remained unchanged [A: largest $t(5) = 1.17$, $P = 0.296$; B: largest $t(5) = -0.877$, $P = 0.421$].

Although we found another very small yet significant mean decrease after follow-up in both groups for number of fixations [A: –5.5 (SD: 1.6, range: 4–8); B: –4.5 (SD: 2.3, range: 1–8)], number of forward saccades [A: –5.5 (SD: 4.5, range: 1–14); B: –3.8 (SD: 2.6, range: 2–8)] and scan-path length [A: –9.1° (SD: 5.4, range: 0.5–15.8); B: –12.5° (SD: 5.8, range: 9.0–23.4)] [A: smallest $t(5) = 2.99$, $P = 0.030$; B: smallest $t(5) = 3.41$, $P = 0.019$], their major decrease was confined to the treatment interval: The pre-post-treatment decrease in these oculomotor measures was consistently and significantly larger (Table 4) than their very small decrease after follow-up, which is also unlikely to reflect any meaningful difference in eye-movement measures [A: smallest $t(5) = 2.95$, $P = 0.032$; B: smallest $t(5) = 2.34$, $P = 0.066$ (marginal significance, possibly due to a large variation in individual pre-post-treatment decreases in scanpath length; Table 4) (two-tailed related samples t-test)].

The treatment effects of text and non-text training were the same (Table 4), which is supported by the significant main effect of time across treatment groups for all oculomotor reading measures [smallest $F(1.3,12.9) = 17.53$, $P = 0.001$] and the absence of a significant effect of treatment group and its interaction with time [largest $F_{\mathrm{trgroup}}(1,10) = 1.81$, $P = 0.208$; largest F_{int} $(1.1,10.9) = 3.16$, $P = 0.101$]. The significant main and interaction effects for number of fixations [$F_{\mathrm{trgroup}}(1,10) = 5.56$, $P = 0.040$; $F_{\mathrm{int}(1.1,11.3)} = 9.00$, $P = 0.010$)] were caused by a significant difference between both groups in mean number of fixations, which was confined to pre-treatment assessment only: Group A showed a higher mean number of fixations (105.3, SD: 18.1) than Group B (76.7, SD: 14.0) [one-way ANOVA, $F(1,13) = 10.89$, $P = 0.006$]. Mean improvements in reading eye-movements did not differ between groups [largest $t(12) = 1.73$, $P = 0.110$). Only the improvements in mean number of fixations differed significantly between treatment groups [A: –38.7, SD: 9.5 (mean decrease relative to pre-treatment assessment: –37%); B: –25.1, SD: 8.1 (mean relative decrease: –33%); $t(12) = 2.88$, $P = 0.014$]. The magnitude of the difference between groups is, however, so small (a 4% difference in the relative decrease of mean number of fixations) that it is unlikely to reflect any meaningful difference in the treatment effects of text and non-text training.

Visual exploration performance

Neither text nor non-text training had an effect on visual exploration performance (A: $n = 20$, B: $n = 20$) (Table 3). Although Group A showed a significant decrease in mean visual exploration time after treatment [$F(1,19) = 6.31$, $P = 0.021$], this improvement was very small [–1.11 s (SD: 2.00)] and is unlikely to reflect any meaningful difference in visual exploration performance; visual exploration performance of all patients was still impaired (except for one patient, see above). We obtained no significant pre-post-treatment changes for Group B [$F(1,19) = 0.33$, $P = 0.573$]. The statistically (but not clinically) significant effect found for Group A explains the significant main effect of time across treatment groups [$F(1,38) = 4.80$, $P = 0.035$]. Yet, again, neither the effect of treatment group nor its

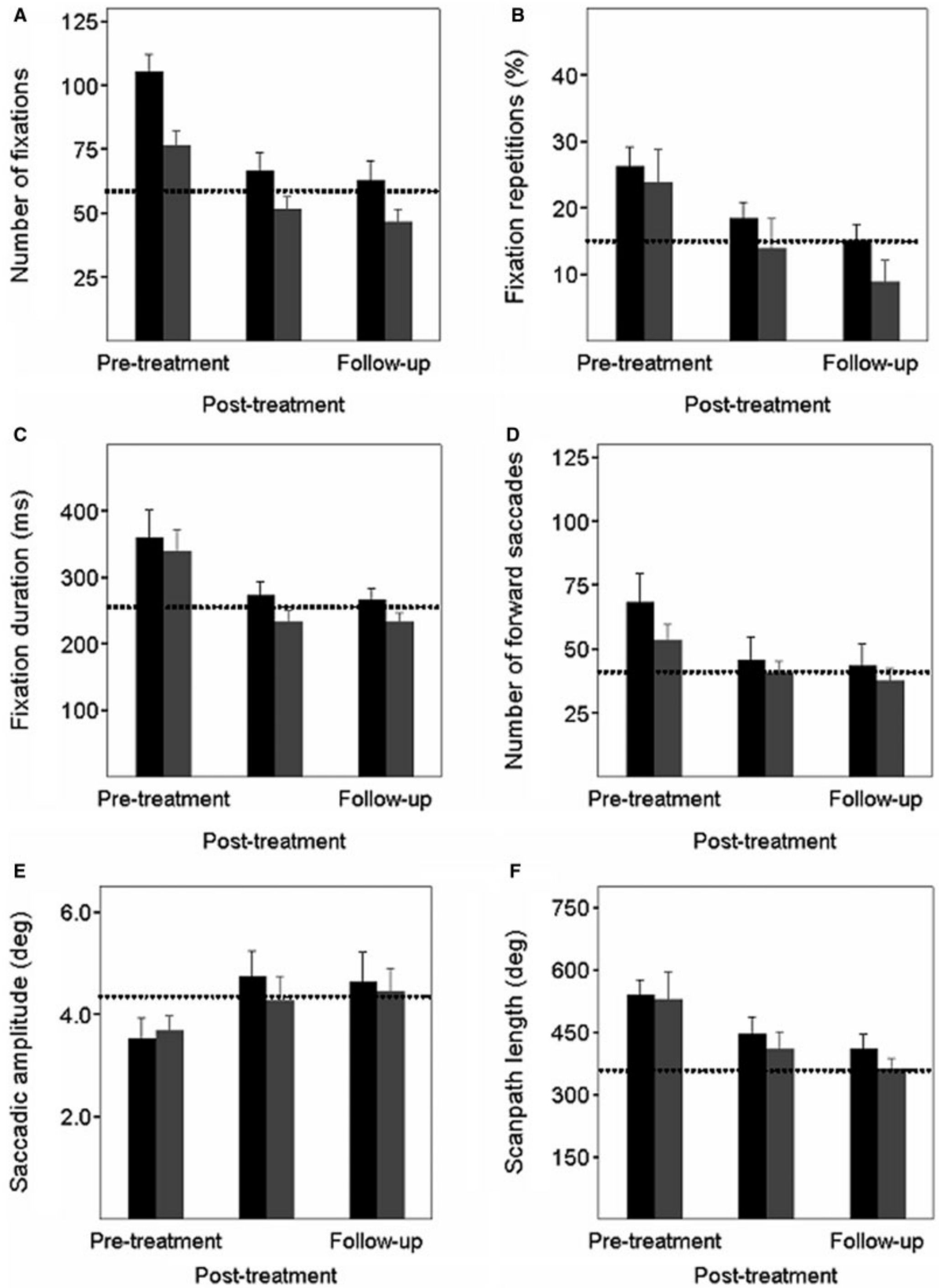

Fig. 2 Mean number of fixations (**A**), fixation repetitions (%) (**B**), mean fixation duration (ms) (**C**), mean number of forward saccades (**D**), mean saccadic amplitude (°) (**E**) and scanpath length (°) (**F**) before and after treatment and at follow-up for both training groups (text training: black bars, non-text training: grey bars; vertical bars indicate 1 SE). Dotted lines indicate average values for normal, age-matched controls ($n = 25$).

interaction with time were significant [$F_{trgroup}(1,38) = 0.48$, $P = 0.492$; $F_{int}(1,38) = 1.92$, $P = 0.174$].

Oculomotor visual exploration measures

Likewise, text and non-text training had no effect on any of the oculomotor visual exploration measures (obtained in seven patients for each treatment group), as indicated by the non-significant of effect of time in both groups [A: largest $F(1,6) = 2.22$, $P = 0.187$; B: largest $F(1,6) = 1.00$, $P = 0.356$] (Table 3). The only significant effect was found for mean number of fixations in Group B [$F(1,6) = 21.15$, $P = 0.004$]; patients showed a very small yet significant decrease after treatment [–2.4 (SD: 1.4); $t(6) = 4.60$, $P = 0.004$], which is, however, unlikely to reflect any meaningful difference in visual exploration performance. The absence of a significant effect of time across treatment groups [largest $F(1,12) = 2.31$, $P = 0.155$], except for mean number of fixations [$F(1,12) = 9.18$, $P = 0.01$], confirmed this result. Again, neither the effect of treatment group nor its interaction with time were significant [largest $F_{trgroup(1,12)} = 1.57$, smallest $P = 0.234$; largest $F_{int(1,12)} = 1.71$, $P = 0.216$].

Visual field extent

None of the patients' visual fields changed between initial, pre- and post-treatment assessments, with the exception of one patient who showed a small increase of 0.5° in visual field sparing after treatment. The same increase was found in six patients of Group A and in two patients of Group B after the follow-up interval. The size of this change however lies within perimetric measurement error. Neither text nor non-text training had an effect on visual field extent (A: $n = 20$, B: $n = 20$): there was no significant effect of time [$F(1.5,29.3) = 2.59$, $P = 0.104$] in Group B, and the significant effect of time for Group A [$F(1.4,25.7) = 10.60$, $P = 0.001$] was accounted for by a small yet significant increase in visual field sparing during follow-up [$t(19) = -3.20$, $P = 0.005$]. This increase also explains the significant main effect of time across treatment groups [$F(1.4,54.9) = 12.65$, $P < 0.001$]. Again, neither the effect of treatment group nor its interaction with time were significant [$F_{trgroup}(1,38) = 0.87$, $P = 0.358$; $F_{int}(1.4,54.9) = 2.87$, $P = 0.081$].

Discussion

The main result of our study is that systematic oculomotor training using time-limited presentation of non-text material has strong therapeutic effects on reading performance and associated eye-movements in patients with hemianopic dyslexia. It is as effective as conventional oculomotor training with text material in alleviating the reading difficulties associated with homonymous visual field disorders. In addition, we found that these treatment effects are specific to reading; there was no transfer of training-related improvement to visual exploration performance and associated eye-movements.

Before treatment, all patients showed considerably reduced reading speeds, visual omission and guessing errors and severely disorganized eye-movement patterns, which is consistent with previous reports on hemianopic dyslexia (Mackensen, 1962; Eber *et al.*, 1987; Kerkhoff *et al.*, 1992; Schoepf and Zangemeister, 1993; Zihl, 1995*a*, 2000; De Luca *et al.*, 1996; Trauzettel-Klosinski and Brendler, 1998; Leff *et al.*, 2000; McDonald *et al.*, 2006; Spitzyna *et al.*, 2007). In agreement with investigations of visual exploration in homonymous visual field disorders, our patients also showed impaired visual exploration performance (Zihl, 1995*b*, 1999, 2000; Tant *et al.*, 2002).

During the period of treatment, non-text reading training led to the same statistically as well as clinically significant improvements in reading performance and eye-movement measures as did text training. These treatment effects were characterized by an increase in reading speed, which was accompanied by a normalization of the oculomotor scan-pattern in reading. Patients made significantly fewer fixations and fixation repetitions and showed much shorter fixation durations. Saccadic amplitudes increased, leading to a much smaller number of forward saccades. After training, patients seemed to extract the same amount of text information by using a much more efficient oculomotor text processing strategy, which is also reflected by the significant decrease in scanpath length.

It is important to note that the improvements in reading performance and associated eye-movements cannot be attributed to spontaneous recovery of the visual field or spontaneous oculomotor adaptation. No patient showed any major change in the parafoveal visual field border. We also could not obtain any change in reading performance between initial and pre-treatment assessment. The major improvement in reading performance and eye-movement parameters was confined to the treatment interval. The additional small increase of reading speed as well as the small decrease of number of fixations, forward saccades and scanpath length after follow-up were very small and are unlikely to reflect any meaningful difference in reading performance and eye-movement parameters; these changes possibly resulted from continued regular reading at home (Zihl, 2000). The improvements in reading with long-term stability (at least for a period of 12 weeks) are therefore attributable to systematic reading-related oculomotor training with text or non-text material.

Our results are consistent with the findings of earlier studies (Zihl *et al.*, 1984; Kerkhoff *et al.*, 1992; Zihl, 1995*a*, 2000; Spitzyna *et al.*, 2007) and confirm the single report on the therapeutic effect of systematic oculomotor practice using time-limited presentation of static text material in the rehabilitation of hemianopic dyslexia (Zihl, 2000). Yet, more importantly, this is the first study to show that the therapeutic effect of this treatment procedure does not critically depend on using words as training material. Systematic reading-related oculomotor training using time-limited presentation of non-text material suffices to facilitate oculomotor adaptation to parafoveal visual field loss, which alleviates the impairments of word identification and oculomotor control during text processing.

Oculomotor adaptation to parafoveal visual field loss is reflected in the training-related changes of oculomotor reading measures (Zihl, 1995*a*, 2000), and is possibly best understood as functional reorganisation of reading eye-movement control. Hemianopic dyslexia is caused by a disturbance of the visual bottom-up and attentional top-down control of text processing and eye-movements (Schuett *et al.*, 2008). This disturbance becomes manifest as a severely disorganized eye-movement pattern in reading, impairments of word identification and slowness of reading. Our results confirm that by oculomotor training, patients can regain the systematic and regular staircase-like eye-movement pattern of normal readers, leading to an improvement in reading performance. These training-related oculomotor changes might emerge as an adaptive solution to the problem of learning how to read efficiently, i.e. to process text information correctly and at the same time as quickly as possible (Reichle and Laurent, 2006), without parafoveal vision. Re-learning reading eye-movement control with parafoveal visual field loss and the consequent improvements in reading performance confirm the importance of precise and effective oculomotor control in reading. It shows that, ultimately, it is not the visual span (the range of letters that can be identified without moving the eyes) (Legge *et al.*, 2007) or simple fixation disengagement (Liversedge *et al.*, 2004) which imposes a limit on reading speed. The effectiveness of reading eye-movement control which brings the visual span 'in action' is decisive. The bottom-up control of text processing and eye-movements, which is based on parafoveal vision in normal readers, can be substituted by an attentional top-down control, suggesting the functional plasticity of the visual, attentional, oculomotor and linguistic systems involved in reading (Schuett *et al.*, 2008).

(Re-)learning reading eye-movement control implies (re-)learning to coordinate not only the visual, attentional and oculomotor processes but also the linguistic processes that control text processing and eye-movements in reading (Rayner and Pollatsek, 1989; Rayner, 1998). Interestingly, learning oculomotor control in beginning readers is accompanied by changes in reading speed and eye-movements (Rayner, 1985, 1986; McConkie *et al.*, 1991) which may be similar to the training-related changes in our patients who re-learned oculomotor control in reading. These developmental changes in reading speed and eye-movements and, thus, in oculomotor control are commonly assumed to follow from linguistic skill acquisition during years of extensive reading practice with linguistic material (Rayner and Pollatsek, 1989). In our patients, however, the training-related changes in reading speed and eye-movements cannot be explained by improvements in linguistic skills. Our patients have already had acquired the linguistic skills necessary for sufficient reading performance. In addition, re-learning reading eye-movement control to make these premorbidly acquired intact linguistic skills useful for reading again does not seem to require reading practice with linguistic material. Our finding that lexical-semantic linguistic processes are not critical to the training-related changes associated with re-learning oculomotor control in skilled readers without parafoveal vision becomes therefore all the more interesting.

This finding also suggests a transfer of training-related oculomotor adaptation from processing visual symbols (Arabic digits) to reading words, sentences and even text passages. No direct practice with text material seems to be necessary for integrating the training-related oculomotor changes into visual and linguistic processing of text information. The lack of transfer to visual exploration indicates, however, that the training-related oculomotor adaptation is nevertheless highly specific and task-dependent. We showed for the first time that the treatment effects of systematic oculomotor training with text (words) or non-text material (Arabic digits) are specific to reading. While this training procedure could significantly improve reading performance and associated eye-movements, it had no effect on patients' visual exploration impairment. Visual exploration performance remained markedly reduced and the associated eye-movement pattern severely disorganized. This lack of transfer between reading and visual exploration suggests that both visuo-motor abilities require specific training for their improvement. Our finding is however not only of high clinical relevance but also indicates that control of visual processing and eye-movements in reading may be mediated by different neural networks than in visual exploration. Although these networks probably overlap, our result illustrates the dissociability of reading- and visual exploration-related visual, attentional and oculomotor processes (Zihl, 1995*a*, *b*, 2000). Task-specificity of oculomotor adaptation may also suggest functional specialisation of the (cortical) oculomotor system in a task-specific way (Alahyane *et al.*, 2007).

Further support stems from the clear double dissociation between spontaneous oculomotor adaptation to homonymous visual field loss in visual exploration and reading. It has been found that patients may successfully overcome their visual exploration impairment while their ability to read remains impaired, and vice versa. In addition, patients are more likely to overcome their impairment in visual exploration (40%) than in reading (20%) (Zihl, 2000). The differences between eye-movement patterns during reading and visual exploration provide additional evidence for our claim; the visually and linguistically structured environment in reading requires a notably different visual sampling strategy than a complex and less systematic scene (Rayner, 1998; Liversedge and Findlay, 2000). Moreover, the oculomotor pattern in visual exploration seems to become adult-like early in infant development (Shea, 1992) whereas the regular staircase-like oculomotor reading pattern requires years of laborious reading practice to develop (Rayner, 1998). These differences in developmental trajectories of eye-movement patterns between visual exploration and reading further substantiate our claim.

A recent report showing that an oculomotor training regime that involved practising visual exploration of pictures had no effect on the reading impairment of patients with parafoveal visual field loss complements our finding (Spitzyna *et al.*, 2007). Hemianopic dyslexia cannot be alleviated by practising any voluntary eye-movements with any visual material. Practising rather smaller, very precise, systematic and regular horizontal saccadic eye-movements with words seems to be essential (Zihl, 2000). Our results show, however, that the treatment effect does not depend on their linguistic properties; their visual properties are essential. This finding is consistent with the significance of visual word-length information for spatial eye-movement control in reading (Rayner, 1998; Inhoff *et al*., 2000; Ducrot and Pynte, 2002; Inhoff *et al*., 2003). Converging evidence stems from studies investigating the effect of pure oculomotor training tasks on reading performance in patients with age-related macular degeneration (Seiple *et al*., 2005) and in patients with reading difficulties of oculomotor and/or visual origin after acquired brain injury (Ciuffreda *et al*., 2006).

Remediation of hemianopic dyslexia may solely depend on perceptual and oculomotor (procedural) learning processes (Ofen-Noy *et al*., 2003), which are modulated by attention. We assume that training-related oculomotor adaptation emerges as a result of motor learning. Motor performance improves through specific practice with error-related feedback (Lisberger, 1988), which enables patients to acquire a flexible eye-movement pattern optimal for efficient text processing without parafoveal vision. Interestingly, the training-related oculomotor changes were characterized by inter-individual variability, suggesting that regaining successful text processing and reading performance may not necessarily depend on one specific combination of oculomotor changes. The same outcome can be reached by different combinations, which is in line with the concept of equifinality in motor learning (Cicchetti and Blender, 2006).

The neural mechanisms mediating these learning processes and thus the therapeutic effect in the rehabilitation of hemianopic dyslexia are still unknown (for a discussion of potential mechanisms, see Schuett *et al*., 2008). Our finding suggests that the cortical structures supporting lexical-semantic processing of words, i.e. the left inferior temporal gyrus (Leff *et al*., 2001) and the left posterior superior temporal gyrus (Binder *et al*., 1997; Powell *et al*., 2006), may not be involved. Whether activation of the left and right fusiform gyrus located in the occipito-temporal region implicated in visual identification of single Arabic digits (Dehaene and Cohen, 1995; Dehaene *et al*., 2004) is critical for mediating the therapeutic effect remains to be investigated.

Although the effects of reading-related oculomotor training using non-text material were not superior to those obtained with text material, there were fewer reports and observations of frustration, distress and tiredness during training with non-text material than with text material. Our clinical observations from training sessions suggest that practising eye-movements with non-text material (Arabic digits) may enhance the rehabilitation experience as patients need not to be confronted with a reading task (and the additional cognitive load associated with it; McCann *et al*., 2000; Shaywitz *et al*., 2001; Lien *et al*., 2008) where they may be distressed by learning to compensate for their visual impairment. As the use of text material confers no advantage in the rehabilitation of hemianopic dyslexia and may be less preferred by patients than non-text material there seems little reason to select text rather than non-text material in this oculomotor training protocol. Reading-related oculomotor training with non-text material may also be a useful treatment option for children with visual field disorders after brain injury (Han *et al*., 2004). Unfortunately, cerebral visual field disorders often remain undiagnosed in the paediatric population (Kedar *et al*., 2006) and no report has dealt with the effects of parafoveal visual field loss on reading in children thus far, let alone potential therapeutic interventions (Zihl and Priglinger, 2002). Children with parafoveal visual field loss are not only confronted with learning to compensate for their visual impairment but have yet to acquire the visual, linguistic and oculomotor skills involved in reading. Since even healthy beginning readers seem to benefit from oculomotor training with non-text material (Lehtimäki and Reilly, 2005), it may be all the more useful to improve oculomotor control in children suffering from visual field disorders.

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