

# Rehabilitation of reading and visual exploration in visual field disorders: transfer or specificity?

Susanne Schuett,<sup>1,2</sup> Charles A. Heywood,<sup>2</sup> Robert W. Kentridge,<sup>2</sup> Ruth Dauner<sup>3</sup> and Josef Zihl<sup>3,4</sup>

1 Department of Clinical, Biological and Differential Psychology, University of Vienna, 1010 Vienna, Austria

2 Department of Psychology, University of Durham, Durham DH1 3LE, UK

3 Department of Psychology, Neuropsychology, Ludwig-Maximilians University Munich, 80802 Munich, Germany

4 Max-Planck-Institute of Psychiatry, 80804 Munich, Germany

Correspondence to: S. Schuett,  
Department of Clinical, Biological and Differential Psychology,  
University of Vienna, Vienna,  
Austria  
E-mail: susanne.schuett@univie.ac.at

Reading and visual exploration impairments in unilateral homonymous visual field disorders are frequent and disabling consequences of acquired brain injury. Compensatory therapies have been developed, which allow patients to regain sufficient reading and visual exploration performance through systematic oculomotor training. However, it is still unclear whether the reading and visual exploration impairments require specific compensatory training for their improvement. We present the first cross-over rehabilitation study to determine whether the training-related performance improvements are task-specific, or whether there is a transfer of training-related improvements between reading and visual exploration. We compared the therapeutic effects of compensatory oculomotor reading and visual exploration training in 36 patients with unilateral homonymous visual field loss in a cross-over design. In addition, we explored whether the training sequence determines the overall treatment outcome. Our findings demonstrate that the training-related improvements in reading and visual exploration are highly specific and task-dependent, and there was no effect of training sequence.

**Keywords:** visual field disorders; reading; visual exploration; rehabilitation; specificity

**Abbreviations:** HVFD = homonymous visual field disorders

## Introduction

Visual field disorders are frequent and disabling functional impairments after brain injury, particularly in older age. Unilateral homonymous visual field disorders (HVFD) resulting from post-chiasmatic visual pathway injury are most common. Patients show severe impairments of reading (hemianopic dyslexia; incidence, 80%) and visual exploration (60%) (Suchoff *et al.*, 2008; Rowe *et al.*, 2009; Zihl, 2011).

Hemianopic dyslexia is an acquired reading disorder whereby patients with HVFD have severe impairments in word recognition and eye movement control during reading despite intact language functions. These deficits become manifest as pronounced slowness of reading, visual omission and guessing errors as well as severely disorganized oculomotor reading pattern. In many patients, reading is almost impossible (Zihl, 1995a, 2011; Trauzettel-Klosinski and Brendler, 1998; Leff *et al.*, 2000; McDonald *et al.*, 2006; Spitzyna *et al.*, 2007; Schuett *et al.*, 2008a, b). The visual

exploration impairment in HVFD disturbs the ability to gain a complete overview of the visual surroundings, causing difficulties in detecting and locating objects, avoiding obstacles as well as in visual–spatial orientation and navigation. This impairment is characterized by considerably increased visual search and exploration times, omissions, as well as, longer and unsystematic oculomotor scanning patterns (Zihl, 1995*b*, 2011; Pambakian *et al.*, 2000; Tant *et al.*, 2002; Mort and Kennard, 2003; Hardiess *et al.*, 2010).

Sufficient spontaneous recovery of the visual field occurs rarely. Although some patients with HVFD spontaneously adapt their eye movements to visual field loss and regain normal reading and visual exploration performance, successful spontaneous oculomotor adaptation is uncommon (Zhang *et al.*, 2006*a*; Zihl, 2011). HVFD and its associated reading and visual exploration impairments are chronic manifestations, which greatly compromise patients' vocational, educational and daily lives (Papageorgiou *et al.*, 2007; Warren, 2009; Zihl, 2011). The rehabilitation of the reading and visual exploration impairments in patients with HVFD is, therefore, of great importance.

Both impairments result from a disturbance of the bottom–up and top–down control of visual information processing and eye movements masquerading as failures of vision (Schuett *et al.*, 2008*a*). The systematic training of compensatory eye movement strategies has proven to be an effective treatment method for improving reading and visual exploration performance in patients with HVFD. This compensatory therapy aims at substituting the lost visual field region by reorganizing the control of visual information processing and eye movements. Patients are trained to intentionally shift their eyes into their blind visual field region, thereby bringing the visual information from the blind field into the seeing field for further processing. They learn to utilize their eye movements to compensate for the visual field defect that enables them to regain adequate reading and visual exploration performance with long-term stability. Training-related improvements are characterized by an increase in reading speed and accuracy as well as reduced visual exploration times and errors. The corresponding re-establishment of systematic oculomotor reading and scanning patterns indicate that these improvements are attributable to training-induced oculomotor adaptation to visual field loss (Zihl, 1995*a, b*, 2011; Schuett *et al.*, 2008*b*, 2009).

Most of the studies investigating this compensatory therapy in HVFD have focused on the visual exploration impairment and evaluated the effect of a specific compensatory visual exploration training (Kerkhoff *et al.*, 1992*a*, 1994; Zihl, 1995*b*, 2011; Nelles *et al.*, 2001; Pambakian *et al.*, 2004; Bolognini *et al.*, 2005; Bouwmeester *et al.*, 2007; Passamonti *et al.*, 2009; Roth *et al.*, 2009; Schofield and Leff, 2009; Keller and Lefin-Rank, 2010; Lane *et al.*, 2010; Mannan *et al.*, 2010). Few studies have dealt with the rehabilitation of hemianopic dyslexia using a specific compensatory reading training (Kerkhoff *et al.*, 1992*b*; Zihl, 1995*a*, 2011; Spitzyna *et al.*, 2007; Schuett *et al.*, 2008*a, b*; Schuett, 2009). In terms of alleviating the visual exploration impairment and hemianopic dyslexia, results have been very promising and confirmed the efficacy of the compensatory therapy approach in HVFD.

However, it is still unclear whether the reading and visual exploration impairments in HVFD require specific compensatory training, i.e. whether training-related performance improvements

are task-specific, or whether there is a transfer between reading and visual exploration and only one type of training is required. There are rare exceptions in the literature on compensatory therapy in HVFD that also investigated the effect of visual exploration training on text reading (Spitzyna *et al.*, 2007; Passamonti *et al.*, 2009; Roth *et al.*, 2009; Keller and Lefin-Rank, 2010; Lane *et al.*, 2010) and, vice versa, the effect of reading training on visual exploration (Schuett *et al.*, 2008*b*). Therefore, to establish the transferability or specificity of compensatory therapy in HVFD, cross-over intervention studies are needed. Addressing this critical gap, not only increases our knowledge about the therapeutic effect of compensatory treatment in HVFD but also about the functional (re-)organization and plasticity of the brain. It also improves current rehabilitation practice and furthers the development of efficient treatment methods for patients with HVFD.

We present the first cross-over rehabilitation study to determine whether the reading and visual exploration impairments in HVFD require specific compensatory training for their improvement, or whether there is a transfer of training-related improvements between reading and visual exploration. We compared the therapeutic effects of compensatory reading and visual exploration training on reading and visual exploration performance in 36 patients with HVFD in a cross-over design. In addition, we explored whether the training sequence in the rehabilitation of the reading and visual exploration impairments in HVFD determines the overall treatment outcome, i.e. whether there is an optimal treatment sequence.

## Subjects and methods

### Participants

Thirty-six patients with left- ( $n = 16$ ) or right-sided ( $n = 20$ ) homonymous visual field loss participated in this study. Mean (SD) age was 63.9 (12.1) years, range (42–83); 16.7% were female, 83.3% male. Homonymous hemianopia was the most frequent visual field defect; 11 patients had a left-sided hemianopia, 14 had a right-sided hemianopia. Three patients had a left-sided, two a right-sided quadrantanopia. Two patients had a left-sided, four a right-sided paracentral scotoma. 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 2.3° (range: 1–6°). In all patients, aetiology of brain injury, as verified by cranial CT and/or MRI, was an infarction in the territory of the posterior cerebral artery causing a lesion to the occipital cortex; two patients had an occipital tumour operation. Time between the occurrence of brain injury and initial assessment was on average 23 weeks (range 4–74). None of the patients had received any treatment for their visual field defect.

Exclusion criteria were associated with 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), aphasia, premorbid reading disorders, pure alexia (vertical word reading test; Zihl, 1995*a*, 2011), impairments of visual–lexical numerical processing (horizontal and vertical number reading; Zihl, 1995*a*, 2011), or verbal memory deficits [Wechsler Memory Scale-Revised (Logical Memory I/II);

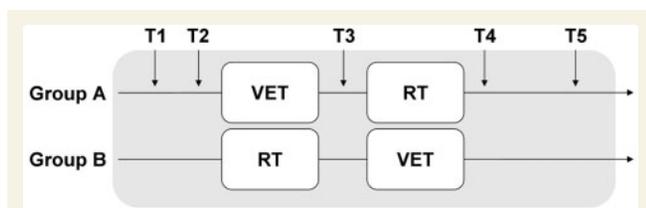
Wechsler, 1987]. None of the patients had visual neglect as assessed by tests in accordance with the Behavioural Inattention Test (line bisection, letter and star cancellation, figure and shape copying, drawing from memory; Halligan *et al.*, 1991). All patients were native German speakers and had at least 5 years of education.

All patients complained of moderate to severe difficulties in reading and visual exploration and showed impaired performance in both domains. Patients were, therefore, systematically treated to compensate better for their visual field loss in reading and visual exploration.

## Study design

Patients were randomly allocated into two treatment groups. Group A ( $n = 18$ ) first received visual exploration training followed by reading training; Group B ( $n = 18$ ) did the converse and first received reading training followed by visual exploration training in a cross-over design (Fig. 1). The number of reading and visual exploration training sessions did not differ between groups [reading training: Group A: 11.6 sessions (SD 4.1), Group B: 12.6 sessions (SD 2.4); visual exploration training: Group A: 12.3 sessions (SD 3.4), Group B: 11.5 sessions (SD 2.4); larger  $t(34) = 0.986$ ,  $P = 0.331$ ]. An individual training session lasted  $\sim 45$  min and consisted of 10 practice units (30 trials each), and short or, if required, longer breaks between units. Before treatment, there were no differences between groups either for demographic and clinical variables or for reading and visual exploration performance (Table 1). Mean (SD) near Snellen visual acuity was 0.97 (0.05), range (0.9–1.0) in both groups.

We used a single subject baseline design with a treatment-free interval before and after training wherein every patient served as his or her own control. Reading performance [corrected reading speed; words per minute (wpm)] and visual exploration performance [visual exploration time (s) and number of errors] were assessed at five time-points: T1, initial assessment; T2, before treatment, i.e. before the first training component [Group A: before visual training, 4.9 weeks after T1 (SD 2.9); Group B: before reading training, 5.9 weeks after T1 (SD 3.7)]; T3, after the first training component (Group A: before reading training; Group B: before visual training); T4, after the second training component; T5, after a follow-up interval [Group A: 11.8 weeks (SD 3.6); Group B: 11.4 weeks (SD 3.4)] (Fig. 1). Visual field assessment was carried out before and after treatment (T2 and T4). Time intervals between assessments did not differ between groups [largest



**Figure 1** Illustration of the study design. Group A first received visual exploration training (VET), then reading training (RT); Group B did the converse and first received reading training, then visual exploration training in a cross-over design. T1–T5 indicate the five time-points at which we assessed reading and visual exploration performance in patients [T1 = initial assessment; T2 = pre-training; T3 = post-training 1 (Group A: after visual exploration training; Group B: after reading training); T4 = post-training 2 (Group A: after reading training; Group B: after visual exploration training); T5 = follow-up].

$t(34) = -0.908$ ,  $P = 0.371$ ]. 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 (Schuett *et al.*, 2008b; Zihl, 2011). Target diameter was  $1.2^\circ$ , its luminance was  $102 \text{ cd/m}^2$ ; background luminance was  $3.2 \text{ cd/m}^2$ . The target was moved with a speed of  $\sim 2^\circ/\text{s}$  from the periphery towards the perimeter's centre. Patients were instructed to fixate on a small red spot of light (diameter:  $0.5^\circ$ ) 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  $0.5^\circ$  and measurement error was  $0.5^\circ$  within the central  $15^\circ$  of the visual field, which is particularly relevant for reading (Table 1). The most important measure, i.e. mean visual field sparing defined as the extent of visual field in degrees between the fovea and the visual field border along the left or right horizontal axes, is reported in the 'Results' section.

## Assessment of reading and visual exploration performance

For assessing reading performance, we used the same standardized reading test as in our previous studies, which we demonstrated to be sensitive to changes in reading performance during treatment (Zihl, 1995a, 2011; Schuett *et al.*, 2008b). Each of the five parallel versions consisted of 200 words of text (font: Arial, 14 pt) 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 (Fig. 2). 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 (wpm); 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 (SD) age 41.3 (13.4) years]. Average corrected reading speed was 161.1 (21.3) wpm (range 121–218 wpm).

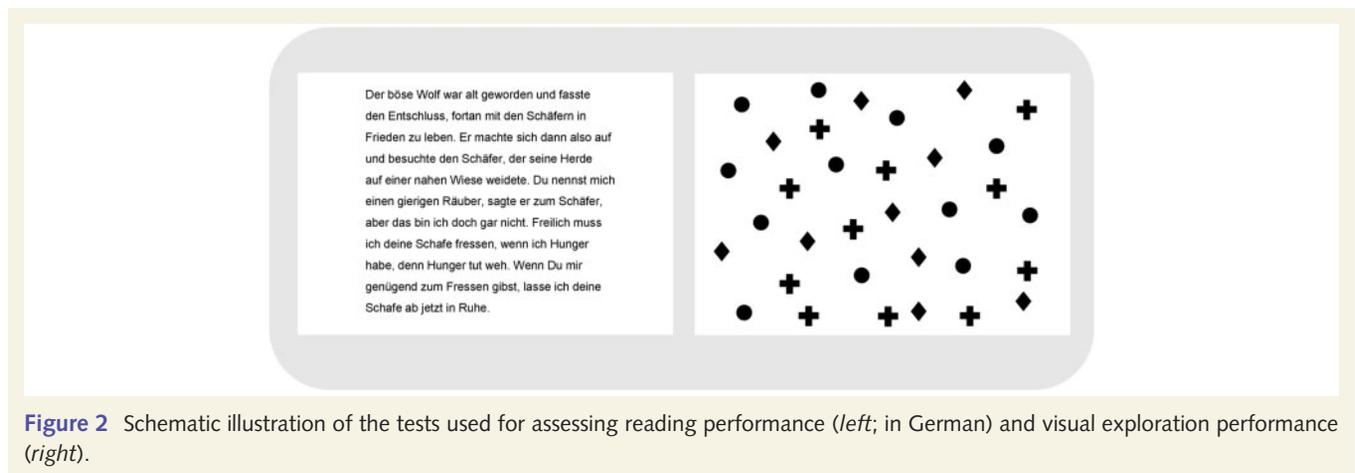
For assessing visual exploration performance, we used the same test as in our previous studies, which we demonstrated to be sensitive to changes in visual exploration performance during treatment (Zihl, 1995b, 2011; Schuett *et al.*, 2008b). We used a cancellation task with 20 black diamonds (targets) randomly embedded among 22 black dots and crosses (distractors) on a sheet of white paper. At a viewing distance of 30 cm, the stimulus array subtended  $44.6^\circ$  horizontally and  $35^\circ$  vertically; stimulus diameter was  $0.8^\circ$  (Fig. 2). Patients were asked to mark all diamonds with a pencil as accurately and as quickly as possible with their right hand; patients were not informed about the number of targets. Visual exploration performance was defined as the time required to perform the task, as well as the number of errors. Normative data were available from 40 control participants [19 females, 21 males; mean (SD) age 46.2 (13.4) years, who required on average 13.7 (1.9) s (range 9.1–18.2 s)] to perform this task without error.

The reading and visual exploration tests were administered under normal daylight conditions. The test sheets were centred at the

**Table 1** Demographic and clinical details and behavioural measurements for both treatment groups

	Group A—training sequence: VET → RT; <i>n</i> = 18; mean (SD), range	Group B—training sequence: RT → VET; <i>n</i> = 18; mean (SD), range	P-value
Age (years)	64.0 (11.1, 44–81)	63.7 (13.3, 42–83)	0.946
Sex (%)			
Female	3 (16.7)	3 (16.7)	
Male	15 (83.3)	15 (83.3)	
Time since lesion (weeks)	26.6 (14.5, 6–57)	20.1 (18.8, 4–74)	0.258
Aetiology (%)			
Posterior infarction	17 (94.4)	17 (94.4)	
Tumour operation	1 (5.6)	1 (5.6)	
Type of visual field loss (%)			
Hemianopia	15 (83.3)	10 (55.6)	
Quadrantopia	1 (5.6)	4 (22.2)	
Paracentral scotoma	2 (11.1)	4 (22.2)	
Side of visual field loss			
Left	9 (50)	7 (38.9)	
Right	9 (50)	11 (61.1)	
Visual field sparing (°) (pretreatment)	2.3 (1.4, 1–6)	2.3 (1.2, 1–4)	1.000
Reading speed (wpm) (pretreatment, T2)	103.8 (34.3, 46–158)	96.3 (35.2, 41–152)	0.522
Visual exploration time (s) (pretreatment, T2)	35.9 (7.6, 23–51)	36.7 (7.0, 27–49)	0.702

Statistical comparisons were made between treatment groups; *P*-values for two-tailed independent *t*-tests are given. RT = reading training; VET = visual exploration training.



patient's body axis at a viewing 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 (Kerckhoff *et al.*, 1990; Zihl, 2011). After treatment, we also asked patients whether they were satisfied with the treatment outcome.

## Method of treatment

The treatment was performed using the software-based reading and visual exploration training programmes as developed by Zihl (2011); training protocol and procedure were similar to our previous studies (Zihl, 1995a, b, 2011; Schuett *et al.*, 2008b). Training material was presented using a LCD monitor with a stimulus display extending 50° horizontally and 42° vertically at a viewing distance of 115 cm.

Ambient room illumination was low (<5 lx) in order to minimize the effects of glare from the monitor. The treatment was administered and supervised by the experimenter, who sat beside the patient to give verbal feedback on reading or visual exploration speed and errors (mainly omissions) during training (supervised learning); errors were always immediately corrected by the experimenter after each trial. In addition, the experimenter ensured that patients did not resort to using head instead of eye movements or 'guessing', both common maladaptive strategies in patients with visual field disorders (Schuett *et al.*, 2008b).

## Reading training

Single words of different lengths, ranging from 3 to 12 letters, were used as training material. Letter and digit size was 2.5°, 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 been shown to allow for comfortable reading and oculomotor training (Zihl, 1995a, 2011; Schuett *et al.*, 2008b). 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 ms to 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. As above, 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. Training was completed when patients reached a defined criterion (at least 90% correct responses) for any level of difficulty used. Patients required on average 12 training sessions, which were carried out within 2–3 weeks for each patient (interval T3–T4 for Group A (11.6 sessions, SD 4.1), T2 and T3 for Group B (12.6 sessions, SD 2.4).

## Visual exploration training

For improving visual exploration, we used standardized versions of the visual search paradigm (parallel and serial search mode), which have proven to be useful in this regard (Zihl, 1995b, 2011). Patients were systematically trained to use larger saccadic eye movements to gain a quick complete visual overview as well as to develop and use a more efficient oculomotor visual exploration or scanning strategy that can be flexibly adapted to the visual-spatial structure of the respective scene or environment. Training material consisted of visual search displays extending 50° horizontally and 42° vertically. We used different target and distractor letters of varying similarity as stimuli. Stimulus size was 2.5°, and we used the same colours for the training material and the monitor background as in the reading training. Each training trial was composed of the presentation of a visual search display. Patients were instructed to fixate on a cross in the centre of the monitor and to search, after its offset, for a single target letter (e.g. 'T') among distractor letters (e.g. 'O's) as accurately and quickly as possible. In target-present trials, the patient was asked to press the left mouse button, in target-absent trials, the right mouse button. Presentation and, thus, visual search time was unlimited (exhaustive visual search). This paradigm allows visual exploration or scanning eye movements to be trained and reinforced by the patient's normal internal visual feedback and feedback given by the experimenter on visual search strategy, time and errors (mainly omissions of targets). Visual exploration training started with the easiest, i.e. parallel search condition (e.g. searching for a 'T' among 'O's, or an 'H' among 'C's) and progressed, via a so-called mixed search condition (transition condition between parallel and serial search; e.g. searching for a 'S' among 'C's, or an 'A' among 'L's), to visual exploration training using more difficult serial

visual search tasks (e.g. searching for an 'O' among 'G's, or a 'B' among 'D's). In addition to varying letter similarity during the course of training, visual search difficulty was also systematically increased by increasing the visual display size, i.e. the number of stimuli, not the display area (15–20-item displays). This training protocol was adjusted to individual reading performance and training progress. An individual training session lasted ~45 min consisting of 10–15 practice units (20 trials each) and short or, if required, longer breaks between units. Training was completed when patients reached a defined criterion (at least 90% correct responses) for any level of difficulty used. Patients required on average 12 training sessions, which were carried out within 2–3 weeks for each patient (Group A: interval T2 and T3, 12.3 sessions, SD 3.4; Group B: interval T3–T4, 11.5 sessions, SD 2.4).

## Statistical analyses

The data were analysed by repeated measures ANOVAs. Separate analyses were performed for reading and visual exploration performance. The details of the analyses carried out, including factor variables, are described in the 'Results' section; for the comparisons, either the largest *F*-value (in cases of non-significant main or interaction effects) or smallest *F*-value (in cases of significant effects) is reported. *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 samples *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

Before treatment (T2), all patients complained of severe difficulties in reading and visual exploration. Their subjective reports were in close agreement with objective test results and were similar in both groups. All patients showed impaired reading and visual exploration performance. Before treatment, mean corrected reading speed was considerably reduced in all patients of both treatment groups (Group A: 103.8 wpm, SD 34.3; Group B: 96.3 wpm, SD 35.2) (Table 2). There were no differences between groups for corrected reading speed [ $t(34) = 0.647$ ,  $P = 0.522$ ]. The reading errors of patients consisted mainly of visual omissions of pre- or suffixes and small words related to the side of visual field loss. Mean visual exploration time as well as number of errors (visual omissions) were also considerably elevated in all patients in both treatment groups (visual exploration time: Group A: 35.9 s, SD 7.64; Group B: 36.9 s, SD 7.0; number of errors: Group A: 3.2, SD 2.77; Group B: 2.9, SD 2.5) (Table 2). There were no significant differences between groups [ $t(34) = -0.386$ ,  $P = 0.702$ ].

After treatment (T4), i.e. after having received both reading training and visual exploration training, all patients reported an improvement in reading and visual exploration performance. Patients described reading and visual exploration to be much quicker, less effortful and much more accurate than before training. When asked whether they were satisfied with the treatment outcome, all patients of both groups replied affirmatively when compared with their performance before treatment. These subjective reports were in close agreement with the treatment effects as verified by objective test results, i.e. by an increase in reading and

**Table 2** Reading and visual exploration performance

	Group A—(training sequence: VET → RT; n = 18)			Group B—(training sequence: RT → VET; n = 18)		
	Reading speed (wpm)	Exploration time (s)	Exploration errors	Reading speed (wpm)	Exploration time (s)	Exploration errors
T2	103.8 (34.3) (46–158)	<b>35.9 (7.6) (23–51)</b>	<b>3.2 (2.8) (0–11)</b>	<b>96.3 (35.2) (41–152)</b>	36.7 (7.0) (27–49)	2.9 (2.5) (0–7)
T3 <sup>a</sup>	<b>105.3 (33.8) (46–160)</b>	<b>18.5 (4.9) (12–34)</b>	<b>0.5 (0.7) (0–2)</b>	<b>124.6 (39.5) (63–175)</b>	<b>36.8 (7.2) (26–48)</b>	<b>3.1 (2.6) (0–9)</b>
T4 <sup>b</sup>	<b>134.2 (36.0) (66–196)</b>	18.9 (5.1) (14–36)	0.4 (0.7) (0–2)	124.7 (39.6) (65–175)	<b>20.1 (3.7) (13–26)</b>	<b>0.4 (0.9) (0–3)</b>
T5	135.8 (37.4) (71–203)	17.8 (5.4) (13–36)	0.5 (0.6) (0–2)	128.0 (38.8) (67–179)	19.7 (4.1) (12–28)	0.7 (0.7) (0–2)
N	161.1 (21.3) (121–218)	13.2 (1.3) (9–17)	0	161.1 (21.3) (121–218)	13.2 (1.3) (9–17)	0

Reading and visual exploration performance before (T2) and after first and second training component (T3, T4) and at follow-up (T5) [mean (SD), range]. Normative data from control samples are given for comparison (N).

RT = reading training; VET = visual exploration training.

Values in bold illustrate the improvements in reading that were associated with reading training but not with visual exploration training as well as the improvements in visual exploration that were associated with visual exploration training but not with reading training (specificity of training-related changes in reading and visual exploration).

a T3: Group A: Post-visual exploration training (improvement in visual exploration only), Group B: Post-reading training (improvement in reading only) (T2–T3).

b T4: Group A: Post-reading training (improvement in reading only), Group B: Post-visual exploration training (improvement in visual exploration only) (T3–T4).

visual exploration speed and accuracy, and were similar in both training groups.

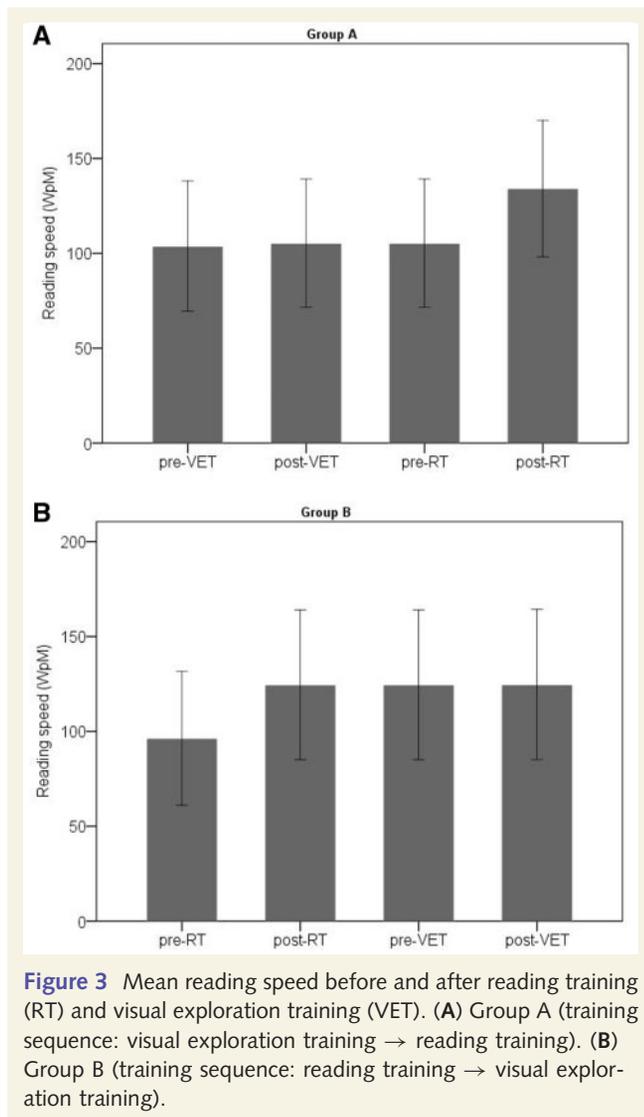
First, we investigated whether the order in which reading training and visual exploration training was carried out had an effect on the changes in reading and visual exploration performance. We used Time as a within-subject factor [before versus after the two training components (T2/T4)] and Group as between-subject factor [Group A (visual exploration training first) versus Group B (reading training first)]. There were no order effects of whether reading training or visual exploration training occurred first on training-related changes [non-significant main and interaction effects: reading performance: larger  $F(1,34) = 0.51$ ,  $P = 0.482$ ; visual exploration performance: larger  $F(1,34) = 0.32$ ,  $P = 0.577$ ]. Thus, patients showed the same improvements in reading and visual exploration performance, irrespective of whether patients first practiced reading and then visual exploration, or vice versa.

Second, we tested whether there were any carry-over effects from reading training or visual exploration training, i.e. whether receiving visual exploration training was beneficial or disadvantageous to the outcome of subsequent reading training (i.e. reading performance) and vice versa. We therefore conducted two repeated measures ANOVAs using Time as a within-subject factor (pre-/post-reading training versus pre-/post-visual exploration training) and Group as a between-subject factor (Group A versus B). We found that the effect of reading training on reading and visual exploration performance did not differ between patients who received visual exploration training before reading training (Group A) and those who received reading training before visual exploration training (Group B) [non-significant main or interaction effects: larger  $F(1,34) = 0.65$ ,  $P = 0.427$ ]. Likewise, the effect of visual exploration training on reading and visual exploration performance did not differ between patients in Groups A and B [non-significant main or interaction effects: larger  $F(1,34) = 0.43$ ,  $P = 0.518$ ]. Thus, practicing reading had no benefits, but also no disadvantages for subsequent visual exploration training in that patients showed a larger, or even a smaller improvement than if reading had not been practiced before, and vice versa.

In summary, there were no order effects or carry-over effects, and the measures for Groups A and B were therefore essentially indistinguishable.

The main result of these analyses was that performing both reading training and visual exploration training led to significant improvements in reading and visual exploration performance [significant effect of Time [before versus after the two training components (T2/T4): smallest  $F(1,34) = 4.84$ ,  $P = 0.035$ ]. In both groups, all patients showed an increase in reading speed and accuracy as well as a considerable decrease in visual exploration time and errors: reading and visual exploration training led to a significant improvement in reading and visual exploration performance, as indicated by a significant effect of Time [before versus after the two training components (T2/T4)] on corrected reading speed and visual exploration time and errors in both groups [Reading: Group A:  $F(4,68) = 21.44$ ,  $P < 0.001$ ; Group B:  $F(4,68) = 81.06$ ,  $P < 0.001$ ; visual exploration time: Group A:  $F(4,68) = 166.49$ ,  $P < 0.001$ , Group B:  $F(4,68) = 139.44$ ,  $P < 0.001$ ; errors: Group A:  $F(4,68) = 17.14$ ,  $P < 0.001$ , Group B:  $F(4,68) = 22.68$ ,  $P < 0.001$ ].

More importantly, we found that these improvements were task specific. Performing reading and visual exploration training led to specific improvements in performance of reading and visual exploration, respectively. Reading training led to a significant increase in reading speed [significant effect of Time (pre- versus post-reading training):  $F(1,34) = 196.88$ ,  $P < 0.001$ ] but did not affect visual exploration times and errors [larger  $F(1,34) = 0.23$ ,  $P = 0.633$ ]. The reading training-related mean improvement in reading speed was 31.4% (SD 15.9), which was significantly larger than the very small change in exploration time [1.3%, SD 7.8;  $t(35) = 10.50$ ,  $P < 0.001$ , two-tailed paired  $t$ -test; Fig. 3]. We obtained the converse pattern of results for visual exploration training. Visual exploration training induced a significant decrease in exploration time and errors [significant effect of Time (pre- versus post-visual exploration training): smaller  $F(1,34) = 48.36$ ,  $P < 0.001$ ]. Although visual exploration training also led to a significant increase in reading speed [ $F(1,34) = 4.84$ ,  $P = 0.035$ ], this



**Figure 3** Mean reading speed before and after reading training (RT) and visual exploration training (VET). (A) Group A (training sequence: visual exploration training → reading training). (B) Group B (training sequence: reading training → visual exploration training).

increase was very small (+1 wpm) and significantly smaller than that after reading training [+29 wpm;  $t(35) = 13.17$ ,  $P < 0.001$ , two-tailed paired  $t$ -test]. The visual exploration training-related mean improvement in exploration time was 46.5% (SD 8.4), which was also significantly larger than the very small change in reading speed [0.9%, SD 2.5;  $t(35) = -30.78$ ,  $P < 0.001$ , two-tailed paired  $t$ -test; Fig. 4]. It is noteworthy that there were no differences in these mean performance improvements in reading and visual exploration, neither for reading training nor for visual exploration training, between patients with left-sided and patients with right-sided visual field loss [non-significant main or interaction effects for side of visual field loss: largest  $F(1,34) = 0.25$ ,  $P = 0.621$ ].

Between initial and pretreatment assessment (T1 and T2) as well as after follow-up (T5), corrected reading speed and visual exploration time and errors remained unchanged in both groups [largest  $t(17) = 2.15$ ,  $P = 0.046$ ]; this almost significant difference was related to a small but significant decrease in visual exploration time (−1 s) in Group A between T1 and T2). Visual field testing

before and after the two training components (T2 and T4) showed that none of the patients' visual field borders changed between pre- and post-treatment assessments in both groups [visual field sparing in degrees of visual angle (T2 and T4); larger  $t(17) = -1.17$ ,  $P = 0.260$ ; Table 1].

## Discussion

Our cross-over rehabilitation study demonstrated the strong therapeutic effect of systematic, compensatory oculomotor reading training and visual exploration training in terms of alleviating the reading and visual exploration impairments in HVFD, respectively. But more importantly, the main result is that the training-related improvements in reading and visual exploration are specific and task dependent. There was no transfer of training-related improvements between reading and visual exploration, indicating the significance of task specificity in compensatory therapy for patients with HVFD. The reading and visual exploration impairments in HVFD require specific compensatory training for their improvement. Further, we found that the training sequence in the rehabilitation of the reading and visual exploration impairments has no effect on the training-related improvements.

Before treatment, all patients showed considerably reduced reading speed and accuracy as well as increased visual exploration times and errors, which is consistent with previous reports on the reading and visual exploration impairments in HVFD (Zihl, 1995a, 2011; Trauzettel-Klosinski and Brendler, 1998; Leff *et al.*, 2000; McDonald *et al.*, 2006; Spitzyna *et al.*, 2007; Schuett *et al.*, 2008a, b; for visual exploration: Zihl, 1995b, 1999, 2011; Pambakian *et al.*, 2000; Tant *et al.*, 2002; Mort and Kennard, 2003; Hardiess *et al.*, 2010). During the period of treatment, reading and visual exploration training led to statistically and clinically significant improvements in reading and visual exploration performance, respectively. This therapeutic effect was characterized by an increase in reading speed and accuracy as well as a decrease in visual exploration time and errors. The improvements in reading and visual exploration performance cannot be attributed to spontaneous recovery of the visual field or spontaneous oculomotor adaptation. Patients' visual fields remained unchanged after treatment, and we also could not obtain any significant change in reading and visual exploration performance between initial and pretreatment assessment or between post-treatment and follow-up assessment. The improvements in reading and visual exploration performance were confined to the treatment interval and characterized by long-term stability (at least for a period of 12 weeks). They are therefore attributable to systematic compensatory oculomotor reading training and visual exploration training.

Although we were not able to analyse and report patients' eye movement data as in our previous studies, which used and investigated exactly the same training protocol and procedure, we can assume that the oculomotor reading and scanning patterns in patients were similar and changed in the same way, leading to a clear improvement in reading and visual exploration performance. We assume that the training-related performance improvements in reading and visual exploration were accompanied by a normalization of the corresponding oculomotor patterns. This is an indicator

of training-related oculomotor adaptation to visual field loss, which has been interpreted as functional reorganization of eye movement control. Compensatory oculomotor training is based on relearning eye movement control with visual field loss, leading to substantial improvements in reading and visual exploration performance. It is possibly best understood as a substitution of the visual bottom-up control of visual information processing and eye movements for a (training-induced) attentional top-down control (Zihl, 1995a, b, 2011; Schuett *et al.*, 2008a, b).

Nonetheless, our study not only confirms earlier studies investigating the therapeutic effect of compensatory visual exploration training (Kerkhoff *et al.*, 1992a, 1994; Zihl, 1995b, 2011; Nelles *et al.*, 2001; Pambakian *et al.*, 2004; Bolognini *et al.*, 2005; Passamonti *et al.*, 2009; Roth *et al.*, 2009; Keller and Lefin-Rank, 2010; Lane *et al.*, 2010; Mannan *et al.*, 2010) and reading training (Kerkhoff *et al.*, 1992b; Zihl, 1995a, 2011; Spitzyna *et al.*, 2007; Schuett *et al.*, 2008b). More importantly, it is the first cross-over rehabilitation study to show that the therapeutic effect of compensatory treatment in HVFD is highly specific and task dependent. Our results demonstrate that systematic compensatory reading training led to significant improvements in reading performance but had no significant effect on visual exploration; likewise, while visual exploration training significantly improved visual exploration performance, it had no significant effect on reading. Neither compensatory oculomotor reading training nor visual exploration training alone is sufficient to improve both abilities. This lack of transfer of training-related performance improvements between reading and visual exploration suggests that both visuo-motor abilities require specific training for their improvement. It is important to note that this lack of transfer also indicates that improving reading performance after reading training did not have a cost on visual exploration performance and vice versa. This implication is important as in some visual retraining studies there have been unfortunate trade-offs in that patients' show improvements in the training task (recognizing objects) at the expense of their performance on another task (recognizing faces; Behrmann *et al.*, 2005).

Our result is consistent with studies that investigated whether compensatory visual exploration training improves not only visual exploration but also reading; the therapeutic effect was confined to visual exploration and did not transfer to text reading (Spitzyna *et al.*, 2007; Lane *et al.*, 2010). This is complemented by our recent finding that the effect of compensatory reading training did not generalize to visual exploration (Schuett *et al.*, 2008b). Evaluations of compensatory visual exploration training involving systematic audiovisual stimulation demonstrated training-related improvements in single-word reading accuracy (Bolognini *et al.*, 2005) and in text reading (Passamonti *et al.*, 2009; Keller and Lefin-Rank, 2010). Yet, single-word reading accuracy is not sufficient for an ecologically valid assessment of hemianopic dyslexia and related training effects. The improvements in text reading induced by visual exploration training were small compared with those induced by compensatory oculomotor reading training. Moreover, the majority of patients investigated in these studies had left-sided visual field loss whose reading impairments are much less severe and respond better to compensatory treatment than those in patients with right-sided field loss (Kerkhoff *et al.*,

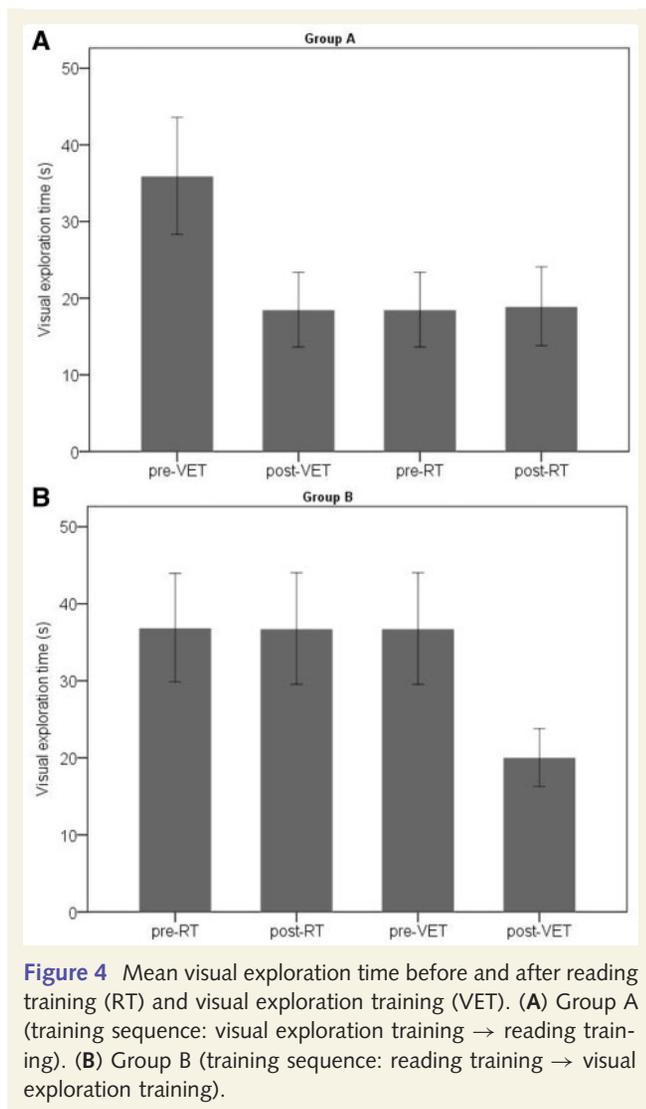
1992b; Zihl, 1995a, 2011; Spitzyna *et al.*, 2007; Schuett *et al.*, 2008b; Schuett, 2009).

Moreover, we found that the cumulative effect of compensatory oculomotor reading and visual exploration training did not differ between patients who first received reading training and those who first received visual exploration training. The training sequence had no significant effect on the training-related improvements. Thus, the outcome of the rehabilitation of the reading and visual exploration impairments in HVFD does not depend on a particular training sequence. This finding is consistent with our recent study investigating spontaneous oculomotor adaptation to simulated visual field loss in reading and visual exploration. We demonstrated that the order of uninstructed reading and visual exploration practice with simulated visual field loss had no effect on consequent oculomotor adaptation and improvements in reading and visual exploration performance (Schuett *et al.*, 2009a, b).

The task-specificity of the treatment effect can possibly be explained best by the fact that reading and visual exploration, though both being visuo-motor abilities, are highly specialized applications of the visual, attentional and oculomotor systems. Processing visual information in reading demands a notably different eye movement strategy from that used for processing a complex and less systematic scene. Moreover, since reading is the process of understanding written language, reading requires not only visual, attentional and oculomotor but also linguistic processes (Rayner, 1998, 2009; Liversedge and Findlay, 2000). Thus, the reading and visual exploration impairments in HVFD cannot be alleviated by training any voluntary eye movements with any visual material.

The rehabilitation of hemianopic dyslexia requires the systematic practice of rather smaller, very precise, systematic and regular horizontal saccadic eye movements with single words or text material. The average saccadic amplitude required for reading is  $\sim 4^\circ$ , at least in our reading tasks used to measure the oculomotor treatment effect (Zihl, 1995a, 2011; Schuett *et al.*, 2008b). Recent evidence shows that the therapeutic effect of compensatory oculomotor reading training does not depend on the linguistic but on the visual properties of words indicating a transfer of training-related improvements from processing visual symbols or numbers to reading words, sentences and text passages (Schuett *et al.*, 2008b). It is important, however, to further increase the natural validity of compensatory reading training and to determine whether the training-related improvements transfer from reading tests to reading books, newspapers, maps as well as to interacting with word- and number-processing software and the Internet (Schuett, 2009). The rehabilitation of the visual exploration impairment, in contrast, requires the systematic practice of large, specific saccadic eye movements and defined oculomotor scanning strategies through use of visual stimulus arrays and visual search displays. The average saccadic amplitude required for visual exploration into the blind hemifield is  $\sim 6^\circ$  and the required oculomotor scanpath in the blind hemifield is  $\sim 50^\circ$ , at least in our visual exploration tasks used to measure the oculomotor treatment effect (Zihl, 1995b, 2011).

Our findings show, however, that there are definite limitations to transfer effects in the rehabilitation of the reading and visual exploration impairments in HVFD. Compensatory oculomotor



**Figure 4** Mean visual exploration time before and after reading training (RT) and visual exploration training (VET). (A) Group A (training sequence: visual exploration training → reading training). (B) Group B (training sequence: reading training → visual exploration training).

reading training improves patients' reading deficits but not their visual exploration impairments, and compensatory oculomotor visual exploration training improves patients' visual exploration impairments but not their reading deficits. In the rehabilitation of visual field disorders using this compensatory oculomotor therapy, patients require two distinct treatments for improving their impaired reading and visual exploration performance.

It remains to be investigated, however, whether our results and implications also apply to the rehabilitation of visual field disorders with a different aetiology. Although posterior cerebral artery infarction, the main aetiology in our patients, is the most common aetiology underlying visual field loss (~70%; Zhang *et al.*, 2006b; Zihl, 2011), our finding needs to be replicated in patients with visual field disorders resulting from other aetiologies, particularly traumatic brain injury, the second common aetiology in this regard (Bruce *et al.*, 2006). It is also important to note that we used a compensatory, eye movement-based therapy to demonstrate the task specificity of the rehabilitation of visual field disorders. Whether other training methods for these visual defects,

particularly visual restitution therapies (Bouwmeester *et al.*, 2007; Schofield and Leff, 2009), might show transfer, remains open for further investigation.

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