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

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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.

Key words: visual field disorders; reading; visual exploration; rehabilitation; specificity

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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 postchiasmatic 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 disorganised oculomotor reading pattern. In many patients, reading is almost impossible (Leff et al., 2000; McDonald et al., 2006; Schuett et al., 2008a, 2008b; Spitzyna et al., 2007; Trauzettel-Klosinski and Brendler, 1998; Zihl, 1995a, 2011). 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 (Hardiess et al., 2010; Mort and Kennard, 2003; Pambakian et al., 2000; Tant et al., 2002; Zihl, 1995b, 2011).

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., 2006a; Zihl, 2011). HVFD and their associated reading and visual exploration impairments are chronic manifestations that 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., 2008a). 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 reorganising 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 which enables them to regain adequate reading and visual exploration performance with long-term stability. Training-related improvements are characterised 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 (Schuett et al., 2008b; Schuett, 2009; Zihl, 1995a, b, 2011).

Most of the studies investigating this compensatory therapy in HVFD have focussed on the visual exploration impairment and evaluated the effect of a specific compensatory visual exploration training (Bolognini et al., 2005; Keller and Lefin-Rank, 2010; Kerkhoff et al., 1992a, 1994; Lane et al., 2010; Mannan et al., 2010; Nelles et al., 2001; Pambakian et al., 2004; Passamonti et al., 2009; Roth et al., 2009; Zihl, 1995b, 2011; for reviews, see Bouwmeester et al., 2007; Schofield & Leff, 2009). Only few studies have dealt with the rehabilitation of hemianopic dyslexia using a specific compensatory reading training (Kerkhoff et al., 1992b; Schuett et al., 2008b; Spitzyna et al., 2007; Zihl, 1995a, 2011; for reviews, see Schuett, 2009; Schuett et al., 2008a). Results in terms of alleviating the visual exploration

impairment and hemianopic dyslexia, respectively, 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 this thriving literature on compensatory therapy in HVFD that also investigated the effect of visual exploration training on text reading (Keller and Lefin-Rank, 2010; Lane et al., 2010; Passamonti et al., 2009; Roth et al., 2009; Spitzyna et al., 2007) and, *vice versa*, the effect of reading training on visual exploration (Schuett et al., 2008b). But to establish the transferability or specificity of compensatory therapy in HVFD, cross-over intervention studies are needed but are still lacking. Addressing this critical gap not only increases our knowledge about the therapeutic effect of compensatory treatment in HVFD but also about the functional (re-)organisation 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.

Methods

Participants

36 patients with left- (n=16) or right-sided (n=20) homonymous visual field loss participated in this study. Mean age was 63.9 years (SD: 12.1, 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, 14 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: $1-6^{\circ}$). 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 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, 1995a, 2011), impairments of visual-lexical numerical processing (horizontal and vertical number reading; Zihl, 1995a, 2011), 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 (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 five 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 (VET) followed by reading training (RT); Group B (n=18) did the converse and first received RT followed by VET in a cross-over design (see Figure 1). The number of reading training and visual exploration training sessions did not differ between groups (RT: Group A: 11.6 sessions (SD: 4.1), Group B: 12.6 sessions (SD: 2.4); VET: 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 ~ 45 minutes; it 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 (see Table 1). Mean near Snellen visual acuity was 0.97 (SD: 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; 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 VT, 4.9 weeks after T1 (SD: 2.9); Group B: before RT, 5.9 weeks after T1 (SD: 3.7)); (T3) after the first training component (Group A: before RT; Group B: before VT); (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)) (see Figure 1). Visual field assessment was carried out before and after treatment (T2, T4). Time intervals between assessments did not differ between groups (largest $t_{(34)}=-0.908$, $p=0.371$). 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° , its luminance was 102 cd/m^2 ;

background luminance was 3.2 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 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 particularly relevant for reading (see also 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, will be 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 (Schuett et al., 2008b; Zihl, 1995a, 2011). Each of the five parallel versions consisted of 200 words of text (font: Arial, 14pt) arranged in 20 double spaced, left-aligned lines printed on a white sheet of paper. The texts were characterised by short sentences and simple syntactic structure and were standardised 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 (see Figure 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 age: 41.3 years (SD: 13.4)). Average corrected reading speed was 161.1 wpm (SD: 21.3, range: 121-218).

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

(Schuett et al., 2008b; Zihl, 1995b, 2011). 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 30cm the stimulus array subtended 44.6° horizontally and 35° vertically; stimulus diameter was 0.8° (see Figure 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 age: 46.2 years (SD: 13.4)), who required on average 13.7s (SD: 1.9, range: 9.1-18.2) to perform this task errorless.

The reading and visual exploration tests were administered under normal daylight conditions. The test sheets were centred at the patient's body axis at a viewing distance of 30cm. 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, Schaub, & Zihl, 1990; Zihl, 2011). After treatment, we also asked patients whether they were satisfied with the treatment outcome.

Method of treatment: Reading training and visual exploration training

The treatment was performed using the software-based reading and visual exploration training programs as developed by Zihl (2011); training protocol and procedure were similar to our previous studies (Schuett et al., 2008b; Zihl, 1995a, 1995b, 2011). Training material was presented using a LCD-monitor with a stimulus display extending 50° horizontally and 42° vertically at a viewing distance of 115cm. Ambient room illumination was low (< 5 lux) in order to minimise 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 shown to allow for comfortable reading and oculomotor training (Schuett et al., 2008b; Zihl, 1995a, 2011). 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 eventually 300 to 400 ms. The final training stage involved the randomised 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 already mentioned, an individual training session lasted ~ 45 minutes; 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-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 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. Os) 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 Os, or an H among Cs) and progressed, via a so-called mixed search condition (transition condition between parallel and serial search; e.g. searching for a S among Cs, or an A among Ls), to visual exploration training using more difficult serial visual search tasks (e.g. searching for an O among Gs, or a B among Ds). 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 minutes 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-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 (A: 103.8 wpm (SD: 34.3), B: 96.3 wpm (SD: 35.2)) (see Table 2, T2). 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: A: 35.9 s (SD: 7.64), B: 36.9 s (SD: 7.0); number of errors: A: 3.2 (SD: 2.77), B: 2.9 (SD: 2.5)) (see Table 2, T2). 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 (RT) and visual exploration training (VET), 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 in the affirmative 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 visual exploration speed and accuracy, and were similar in both training groups.

First, we investigated whether the order in which RT and VET was carried out had an effect on the changes in reading and visual exploration performance. We used Time as a within-subject factor (before vs. after the two training components (T2/T4)) and Group as between-subject factor (Group A (VET first) vs. Group B (RT first)). There were no order effects of whether RT or VET 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.

Secondly, we tested whether there were any carry-over effects from RT or VET, i.e. whether receiving VET was beneficial or disadvantageous to the outcome of subsequent RT (i.e. reading performance) and *vice versa*. We therefore conducted two repeated measures ANOVAs using Time as a within-subject factor (pre-/post-RT vs. pre-/post-VET) and Group as a between-subject factor (Group A vs. B). We found that the effect of RT on reading and visual exploration performance did not differ

between patients who received VET before RT (Group A) and those who received RT before VET (Group B) (non-significant main or interaction effects: larger $F_{(1,34)}=0.65$, $p=0.427$). Likewise, the effect of VET on reading and visual exploration performance did not differ between patients in Group A and Group 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 VET 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 RT and VET led to significant improvements in reading and visual exploration performance (significant effect of Time (before vs. 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 vs. 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 RT and VET led to specific improvements in performance of reading and visual exploration, respectively. RT led to a significant increase in reading speed (significant effect of Time (pre- vs. post-RT): $F_{(1,34)}=196.88$, $p<0.001$) but did not affect visual exploration times and errors (larger $F_{(1,34)}=0.23$, $p=0.633$). The RT-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; see also Figure 3). We obtained the converse pattern of results for VET. VET induced a significant decrease in exploration time and errors (significant effect of Time (pre- vs. post-VET): smaller $F_{(1,34)} = 48.36$, $p < 0.001$). Although VET also led to a significant increase in reading speed ($F_{(1,34)} = 4.84$, $p = 0.035$), this increase was very small (+1 wpm) and significantly smaller than that after RT (+29 wpm; $t_{(35)} = 13.17$, $p < 0.001$, two-tailed paired t-test). The VET-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; see also Figure 3). It is noteworthy that there were no differences in these mean performance improvements in reading and visual exploration, neither for RT nor for VET, 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 pre-treatment assessment (T1, 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 (-1s) in Group A between T1 and T2). Visual field testing before and after the two training components (T2, 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, T4); larger $t_{(17)} = -1.17$, $p = 0.260$; see also 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 (for reading, see Leff et al., 2000; McDonald et al., 2006; Schuett et al., 2008a, 2008b; Spitzyna et al., 2007; Trauzettel-Klosinski and Brendler, 1998; Zihl, 1995a, 2011; for visual exploration, see Hardiess et al., 2010; Mort and Kennard, 2003; Pambakian et al., 2000; Tant et al., 2002; Zihl, 1995b, 1999, 2011). 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 pre-treatment 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 analyze and report patients' eye-movement data as in our previous studies that 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 re-learning 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 (Schuett et al., 2008a, 2008b; Zihl, 1995a, 1995b, 2011).

Yet, our study not only confirms earlier studies investigating the therapeutic effect of compensatory visual exploration training (Bolognini et al., 2005; Keller and Lefin-Rank, 2010; Kerkhoff et al., 1992a, 1994; Lane et al., 2010; Mannan et al., 2010; Nelles et al., 2001; Pambakian et al., 2004; Passamonti et al., 2009; Roth et al., 2009; Zihl, 1995b, 2011) and reading training (Kerkhoff et al., 1992b; Schuett et al., 2008b; Spitzyna et al., 2007; Zihl, 1995a, 2011). 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; see 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 (Lane et al., 2010; Spitzyna et al., 2007). This is complemented by our recent finding that the effect of a compensatory reading training did not generalise 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 (Keller and Lefin-Rank, 2010; Passamonti et al., 2009). 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; Schuett et al., 2008b; Spitzyna et al., 2007; Zihl, 1995a, 2011; see also 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, 2009b).

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 (Liversedge & Findlay, 2000; Rayner, 1998, 2009). 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 practise 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 (e.g., Schuett et al., 2008b; Zihl, 1995a, 2011). 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 ecological 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 (e.g., 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 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 ($\sim 70\%$, see 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 (for reviews, see Bouwmeester et al., 2007; Schofield & Leff, 2009), might show transfer, remains open for further investigation.

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For Peer Review

References

- Alahyane N, Salemme R, Urquizar C, Cotti J, Guillaume A, Vercher JL et al. Oculomotor plasticity: Are mechanisms of adaptation for reactive and voluntary saccades separate? *Brain Res* 2007; 1135: 107–21.
- Behrmann M, Marotta J, Gauthier I, Tarr MJ, McKeeff T J. Behavioral change and its neural correlates in visual agnosia after expertise training. *J Cogn Neurosci* 2005; 17: 554–68.
- Bolognini N, Rasi F, Coccia M, Ládavas E. Visual search improvement in hemianopic patients after audio-visual stimulation. *Brain* 2005; 128: 2830–42.
- Bouwmeester L, Heutink J, Lucas C. The effect of visual training for patients with visual field defects due to brain damage: A systematic review. *J Neurol, Neurosurg Psychiatry* 2007; 78: 555–64.
- Bruce BB, Zhang X, Kedar S, Newman NJ, Biousse V. Traumatic homonymous hemianopia. *Journal of Neurology, Neurosurgery and Psychiatry* 2006; 77: 986–8.
- Halligan PW, Cockburn J, Wilson BA. The behavioural assessment of visual neglect. *Neuropsychol Rehabil* 1991; 1: 5–32.
- Hardiess G, Papageorgiou E, Schiefer U, Mallot HA. Functional compensation of visual field deficits in hemianopic patients under the influence of different task demands. *Vis Res* 2010; 50: 1158–1172.
- Ilg R, Wohlschläger AM, Gaser C, Liebau Y, Dauner R, Wöller A et al. Gray matter increase induced by practice correlates with task-specific activation: A combined functional and morphometric magnetic resonance imaging study. *J Neurosci* 2008; 28: 4210–5.
- Jones S, Nyberg L, Sandblom J, Stigsdotter Neely A, Ingvar M, Petersson KM et al. Cognitive and neural plasticity in aging: General and task-specific limitations. *Neurosci Biobehav Rev* 2006; 30: 864–71.
- Kassubek J, Schmidtke K, Kimmig H, Lücking CH, Greenlee MW. Changes in cortical activation during mirror reading before and after training: an fMRI study of procedural learning. *Cogn Brain Res* 2001; 10: 207–17.

- Keller I, Lefin-Rank G. Improvement of visual search after audiovisual exploration training in hemianopic patients. *Neurorehabil Neural Repair* 2010; 24: 666–73.
- Kerkhoff G, Münßinger U, Haaf E, Eberle-Strauss G, Stögerer E. Rehabilitation of homonymous scotomata in patients with postgeniculate damage of the visual system: saccadic compensation training. *Restor Neurol Neurosci* 1992a; 4: 245–54.
- Kerkhoff G, Müßinger U, Eberle-Strauss G, Stögerer E. Rehabilitation of hemianopic alexia in patients with postgeniculate visual field disorders. *Neuropsychol Rehabil* 1992b; 2: 21–42.
- Kerkhoff G, Münßinger U, Meier EK. Neurovisual rehabilitation in cerebral blindness. *Arch Neurol* 1994; 51: 474–81.
- Kerkhoff G, Schaub J, Zihl J. Die Anamnese zerebral bedingter Sehstörungen [Anamnesis of cerebral visual disorders]. *Nervenarzt* 1990; 61: 711–8.
- Lane AR, Smith DT, Ellison A, Schenk T. Visual exploration training is no better than attention training for treating hemianopia. *Brain* 2010; 133: 1717–28.
- Leff AP, Scott SK, Crewes H, Hodgson TL, Cowey A, Howard D et al. Impaired reading in patients with right hemianopia. *Ann Neurol* 2000; 47: 171–8.
- Lisberger SG. The neural basis for learning of simple motor skills. *Science* 1988; 243: 728–34.
- Liversedge SP, Findlay JM. Saccadic eye movements and cognition. *Trends Cog Sci* 2000; 4: 6–14.
- Mannan SK, Pambakian ALM, Kennard C. Compensatory strategies following visual search training in patients with homonymous hemianopia: an eye movement study. *J Neurol* 2010; 257: 1812–21.
- McDonald SA, Spitzyna G, Shillcock R, Wise RJS, Leff AP. Patients with hemianopic alexia adopt an inefficient eye movement strategy when reading text. *Brain*: 2006; 129: 158–67.
- Mort DJ, Kennard C. Visual search and its disorders. *Curr Opin Neurol* 2003; 16: 51–7.
- Nelles G, Esser J, Eckstein A, Tiede A, Gerhard H, Diener H. Compensatory visual field training for patients with hemianopia after stroke. *Neurosci Lett* 2001; 306: 189–92.

- Nelles G, De Greiff A, Pscherer A, Forsting M, Gerhard H, Esser J et al. Cortical activation in hemianopia after stroke. *Neurosci Lett* 2007; 426: 34–8.
- Ofen-Noy N, Dudai Y, Karni A. Skill learning in mirror reading: How repetition determines acquisition. *Cogn Brain Res* 2003; 17: 507–21.
- Papageorgiou E, Hardiess G, Schaeffel F, Wiethoelter H, Karnath HO, Mallot H et al. Assessment of vision-related quality of life in patients with homonymous visual field defects. *Graefes Arch Clin Exp Ophthalmol* 2007; 245: 1749–58.
- Pambakian ALM, Wooding DS, Patel N, Morland AB, Kennard C, Mannan SK. Scanning the visual world: A study of patients with homonymous hemianopia. *J Neurol Neurosurg Psychiatry* 2000; 69: 751–9.
- Pambakian ALM, Mannan SK, Hodgson TL, Kennard C. Saccadic visual search training: a treatment for patients with homonymous hemianopia. *J Neurol Neurosurg Psychiatry* 2004; 75: 1443–8.
- Passamonti C, Bertini C, Ládas E. Audio-visual stimulation improves oculomotor patterns in patients with hemianopia. *Neuropsychologia* 2009; 47: 546–55.
- Poldrack RA, Desmond JE, Glover GH, Gabrieli JDE. The neural basis of visual skill learning: an fMRI study of mirror reading. *Cereb Cortex* 1998; 8: 1–10.
- Poldrack RA, Gabrieli JDE. Characterizing the neural mechanisms of skill learning and repetition priming: evidence from mirror reading. *Brain* 2001; 124: 67–82.
- Rayner K. Eye movements in reading and information processing: 20 years of research. *Psychol Bull* 1998; 124: 372–422.
- Rayner K. The Thirty Fifth Sir Frederick Bartlett Lecture: Eye movements and attention in reading, scene perception, and visual search. *Quart J Exp Psychol* 2009; 62: 1457–1506.
- Roth T, Sokolov A, Messias A, Roth P, Weller M, Trauzettel-Klosinski S. Comparing explorative saccade and flicker training in hemianopia: a randomized controlled study. *Neurology* 2009; 72: 324–31.

- Rowe F, Brand D, Jackson CA, Price A, Walker L, Harrison S et al. Visual impairment following stroke: Do stroke patients require vision assessment? *Age Ageing* 2009; 38: 188–193.
- Schofield T, Leff A. Rehabilitation of hemianopia. *Curr Opin Neurol* 2009; 22: 36–40.
- Schuett S. The rehabilitation of hemianopic dyslexia. *Nature Rev Neurol* 2009; 5: 427–37.
- Schuett S, Heywood CA, Kentridge RW, Zihl J. The significance of visual information processing in reading: Insights from hemianopic dyslexia. *Neuropsychologia* 2008a; 46: 2441–58.
- Schuett S, Heywood CA, Kentridge RW, Zihl J. Rehabilitation of hemianopic dyslexia: are words necessary for re-learning oculomotor control? *Brain* 2008b; 131: 3156–68.
- Schuett S, Kentridge RW, Zihl J, Heywood CA. Adaptation of eye movements to simulated hemianopia in reading and visual exploration: Transfer or specificity? *Neuropsychologia* 2009a; 47: 1712–20.
- Schuett S, Kentridge RW, Zihl J, Heywood CA. Are hemianopic reading and visual exploration impairments visually elicited? New insights from eye movements in simulated hemianopia. *Neuropsychologia* 2009b; 47: 733–46.
- Shea SL. Eye movements: Developmental aspects. In E Chekaluk, K Llewellyn (eds.), *The role of eye movements in perceptual processes*. Amsterdam: North-Holland 1992; 239–306.
- Spitzyna GA, Wise RJS, McDonald SA, Plant G, Kidd D, Crewes H, et al. Optokinetic therapy improves text reading in patients with hemianopic alexia: A controlled trial. *Neurology* 2007; 68: 1922–30.
- Suchoff IB, Kapoor N, Ciuffreda KJ, Rutner D, Han E, Craig S. The frequency of occurrence, types, and characteristics of visual field defects in acquired brain injury: a retrospective analysis. *Optometry* 2008; 79: 259–65.
- Tant MLM, Cornelissen FW, Kooijman AC, Brouwer WH. Hemianopic visual field defects elicit hemianopic scanning. *Vis Res* 2002; 42: 1339–48.

- Trauzettel-Klosinski S, Brendler K. Eye movements in reading with hemianopic field defects: the significance of clinical parameters. *Graefes Arch Clin Exp Ophthalmol* 1998; 236: 91–102.
- Vistech contrast sensitivity test. Dayton, Ohio: Vistech Consultants, Inc. 1988.
- Warren M. Pilot study on activities of daily living limitations in adults with hemianopsia. *Am J Occup Ther* 2009; 63: 626-33.
- Wechsler D. WMS-R: Wechsler Memory Scale Revised (Manual). San Antonio, TX: The Psychological Corporation 1987.
- Zhang X, Kedar S, Lynn MJ, Newman NJ, Biousse V. Natural history of homonymous hemianopia. *Neurology* 2006a; 66: 901–5.
- Zhang X, Kedar S, Lynn MJ, Newman NJ, Biousse V. Homonymous hemianopias: Clinical–anatomic correlations in 904 cases. *Neurology* 2006b; 66: 906–10.
- Zihl J. Eye movement patterns in hemianopic dyslexia. *Brain* 1995a; 118: 891–912.
- Zihl J. Visual scanning behaviour in patients with homonymous hemianopia. *Neuropsychologia* 1995b; 33: 287–303.
- Zihl J. Rehabilitation of visual disorders after brain injury, 2nd ed. Hove, UK: Psychology Press 2011.

Tables

Table 1 Demographic and clinical details and behavioural measurements for both treatment groups [mean (SD, range)]. VET: visual exploration training, RT: reading training. Statistical comparisons were made between treatment groups; p-values for two-tailed independent t-tests are given.

| | Group A (training sequence: VET → RT; n=18) | Group B (training sequence: RT → VET; n=18) | |
|--|---|---|---------|
| Age (years) | 64.0 (11.1, 44-81) | 63.7 (13.3, 42-83) | p=.946 |
| Sex | | | |
| <i>Female</i> | 3 (16.7%) | 3 (16.7%) | |
| <i>Male</i> | 15 (83.3%) | 15 (83.3%) | |
| Time since lesion (weeks) | 26.6 (14.5, 6-57) | 20.1 (18.8, 4-74) | p=.258 |
| Aetiology | | | |
| <i>Posterior infarction</i> | 17 (94.4%) | 17 (94.4%) | |
| <i>Tumor operation</i> | 1 (5.6%) | 1 (5.6%) | |
| Type of visual field loss | | | |
| <i>Hemianopia</i> | 15 (83.3%) | 10 (55.6%) | |
| <i>Quadranopia</i> | 1 (5.6%) | 4 (22.2%) | |
| <i>Paracentral scotoma</i> | 2 (11.1%) | 4 (22.2%) | |
| Side of visual field loss | | | |
| <i>Left</i> | 9 (50%) | 7 (38.9%) | |
| <i>Right</i> | 9 (50%) | 11 (61.1%) | |
| Visual field sparing (°) (pre-treatment) | 2.3 (1.4, 1-6) | 2.3 (1.2, 1-4) | p=1.000 |
| Reading speed (wpm) (pre-treatment, T2) | 103.8 (34.3, 46-158) | 96.3 (35.2, 41-152) | p=.522 |
| Visual exploration time (s) (pre-treatment; T2) | 35.9 (7.6, 23-51) | 36.7 (7.0, 27-49) | p=.702 |

Table 2 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).

VET: visual exploration training, RT: reading training.

The grey highlighting illustrates the improvements in reading that were associated with RT but not with VET as well as the improvements in visual exploration that were associated with VET but not with RT (specificity of training-related changes in reading and visual exploration).

| | 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] | 35.9 (7.6) [23-51] | 3.2 (2.8) [0-11] | 96.3 (35.2) [41-152] | 36.7 (7.0) [27-49] | 2.9 (2.5) [0-7] |
| T3* | 105.3 (33.8) [46-160] | 18.5 (4.9) [12-34] | 0.5 (0.7) [0-2] | 124.6 (39.5) [63-175] | 36.8 (7.2) [26-48] | 3.1 (2.6) [0-9] |
| T4** | 134.2 (36.0) [66-196] | 18.9 (5.1) [14-36] | 0.4 (0.7) [0-2] | 124.7 (39.6) [65-175] | 20.1 (3.7) [13-26] | 0.4 (0.9) [0-3] |
| 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 |

*T3: Group A: Post-VET (improvement in visual exploration only), Group B: Post-RT (improvement in reading only) [T2-T3]

**T4: Group A: Post-RT (improvement in reading only), Group B: Post-VET (improvement in visual exploration only) [T3-T4]

Figures

Fig. 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 RT, then VET 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 VET; Group B: after RT); T4: post-training 2 (Group A: after RT; Group B: after VET); T5: follow-up).

Fig. 2 Schematic illustration of the tests used for assessing reading performance (left image) and visual exploration performance (right image).

Fig. 3 Mean reading speed before and after reading training (RT) and visual exploration training (VET). 3A: group A (training sequence: VET → RT), 3B: group B (training sequence: RT → VET)

Fig. 4 Mean visual exploration time before and after reading training (RT) and visual exploration training (VET). 4A: group A (training sequence: VET → RT), 4B: group B (training sequence: RT → VET)

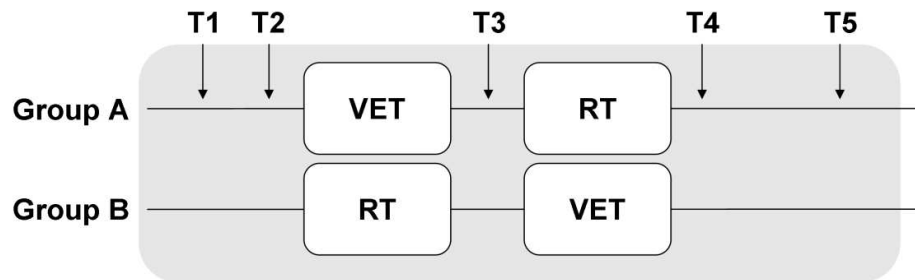


Fig. 1 Illustration of the study design. Group A first received visual exploration training (VET), then reading training (RT); Group B did the converse and first received RT, then VET in a cross-over design. T1-T5 indicate the five time points at which we assessed reading and visual exploration performance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

102x36mm (300 x 300 DPI)

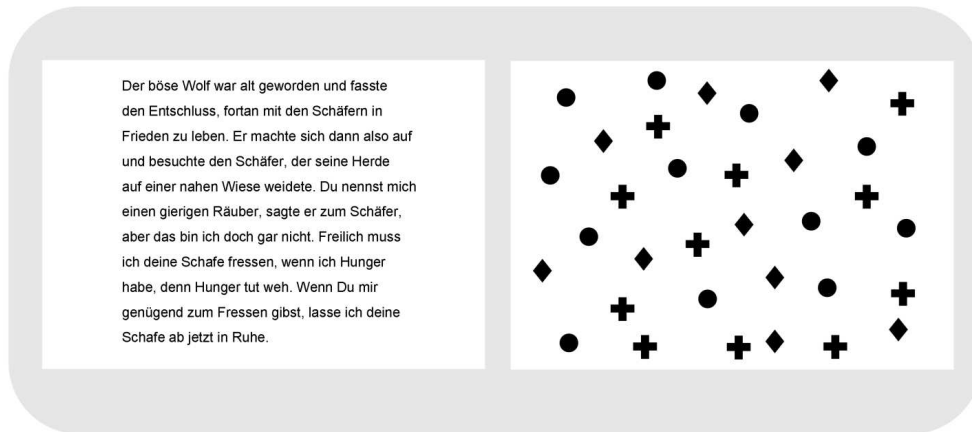


Fig. 2 Schematic illustration of the tests used for assessing reading performance (left image) and visual exploration performance (right image).
123x57mm (300 x 300 DPI)

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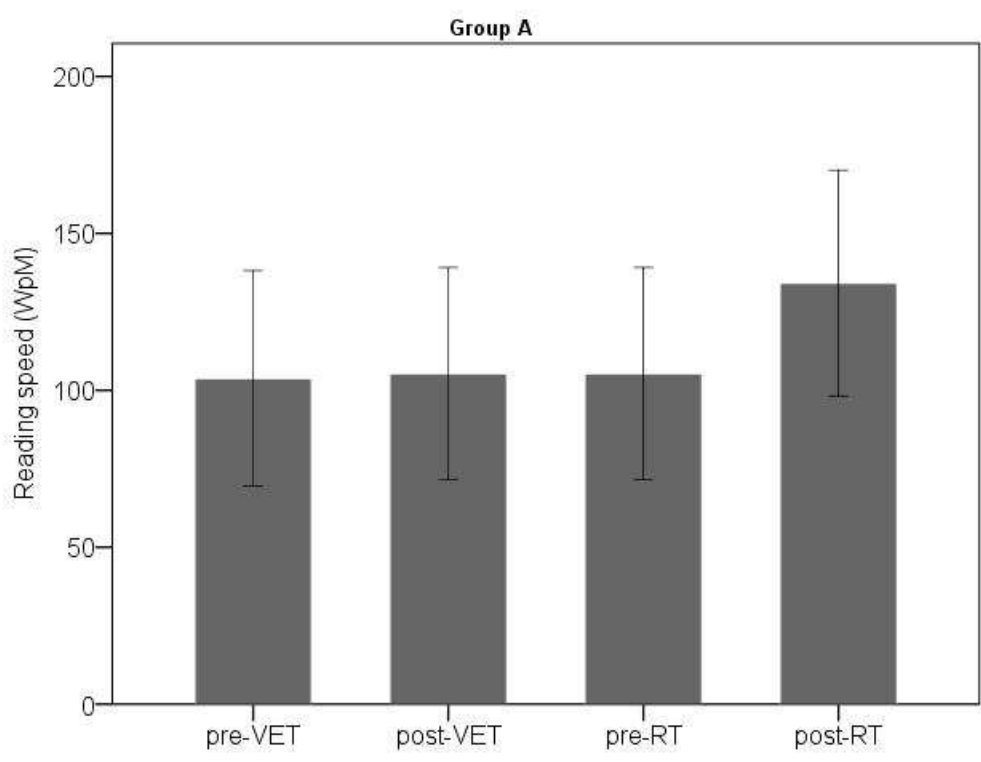


Fig. 3 Mean reading speed before and after reading training (RT) and visual exploration training (VET). 3A: group A (training sequence: VET --> RT)
220x176mm (72 x 72 DPI)

view

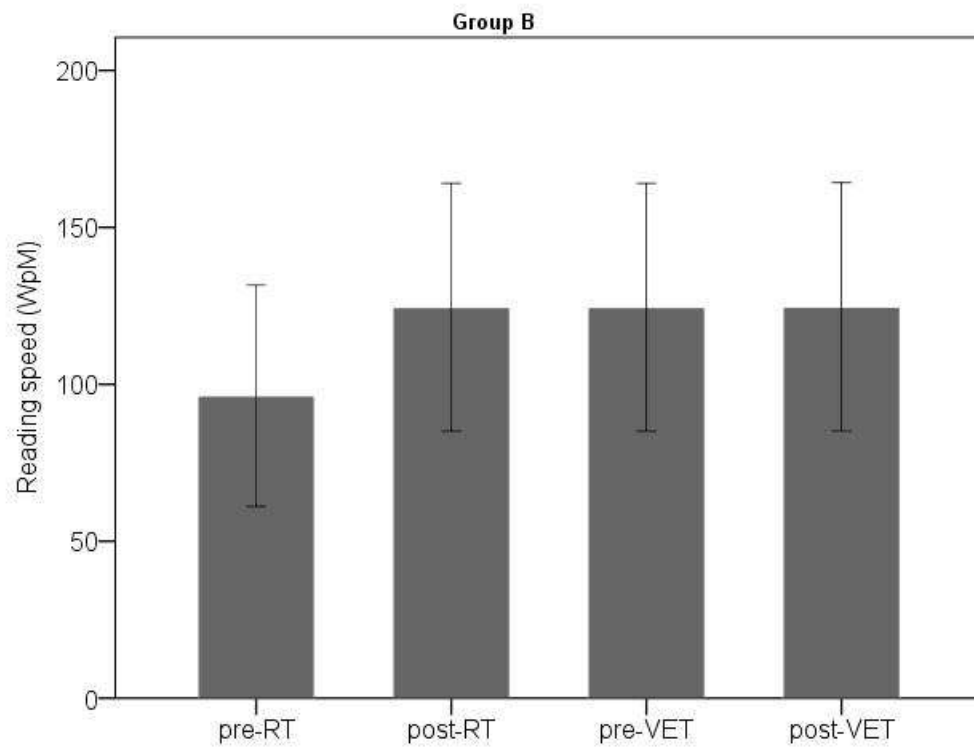


Fig. 3 Mean reading speed before and after reading training (RT) and visual exploration training (VET). 3B: group B (training sequence: RT --> VET)
220x176mm (72 x 72 DPI)

view

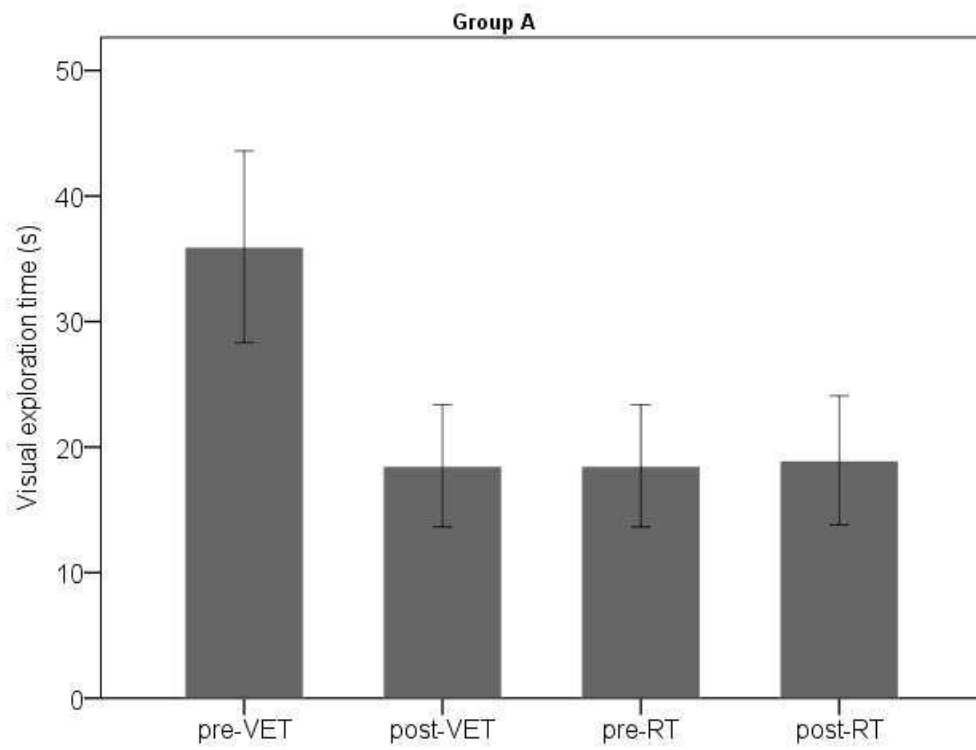


Fig. 4 Mean visual exploration time before and after reading training (RT) and visual exploration training (VET). 4A: group A (training sequence: VET --> RT)
220x176mm (72 x 72 DPI)

view

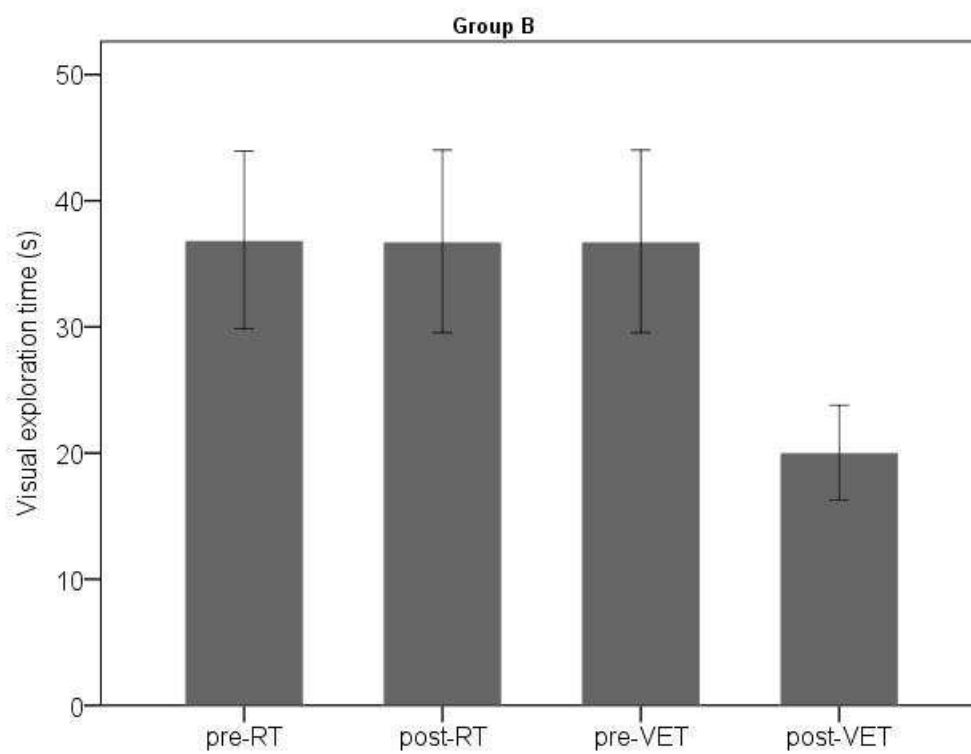


Fig. 4 Mean visual exploration time before and after reading training (RT) and visual exploration training (VET). 4B: group B (training sequence: RT --> VET)
220x176mm (72 x 72 DPI)

view