

Adaptation of eye-movements to simulated hemianopia in reading and visual exploration: Transfer or specificity?

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ABSTRACT

Reading and visual exploration impairments in unilateral homonymous hemianopia are well-established clinical phenomena. Spontaneous adaptation of eye-movements to the visual field defect leads to improved reading and visual exploration performance. Yet, it is still unclear whether oculomotor adaptation to visual field loss is task-specific or whether there is a transfer of adaptation-related improvements between reading and visual exploration. We therefore simulated unilateral homonymous hemianopia in healthy participants and explored the specificity with which oculomotor adaptation to this pure visual-sensory dysfunction during uninstructed reading or visual exploration practice leads to improvements in both abilities. Our findings demonstrate that there is no transfer of adaptation-related changes of eye-movements and performance improvements between reading and visual exploration. Efficient oculomotor adaptation to visual field loss is highly specific and task-dependent.

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1. Introduction

Unilateral homonymous hemianopia (HH) is the most frequent visual disorder after brain damage (Zihl, 2000). It is commonly caused by posterior cerebral artery infarction affecting the postchiasmatic visual pathway. In HH, vision is lost in both monocular hemifields contralateral to the side of brain injury (Zhang, Kedar, Lynn, Newman, & Biousse, 2006a; Zihl, 2000). Homonymous visual field defects are chronic manifestations since sufficient spontaneous recovery of the visual field is seldom (Zhang, Kedar, Lynn, Newman, & Biousse, 2006b; Zihl & Kennard, 1996). The majority of patients show persistent and severe impairments of reading (i.e., hemianopic dyslexia) (Schuett, Heywood, Kentridge, & Zihl, 2008a) and visual exploration (Zihl, 2000).

The cardinal symptoms of hemianopic dyslexia are slowed reading, visual omission and guessing errors as well as a severely altered reading eye-movement pattern (e.g., Leff et al., 2000; McDonald, Spitzyna, Shillcock, Wise, & Leff, 2006; Spitzyna et al., 2007; Trauzettel-Klosinski & Brendler, 1998; Zihl, 1995a, 2000). The visual exploration impairment is characterised by considerably increased exploration times, target omissions as well as longer and unsystematic oculomotor scanning patterns (e.g., Mort & Kennard, 2003; Pambakian et al., 2000; Tant, Cornelissen, Kooijman, & Brouwer,

2002; Zihl, 1995b, 1999, 2000). These hemianopic reading and visual exploration impairments have been reported early in the literature and are now well-established clinical phenomena (for early clinical reports, see Mauthner, 1881; Pfeifer, 1919; Poppelreuter, 1917/1990; Wilbrand, 1907).

Spontaneous adaptation of eye-movements to visual field loss and consequent improvements in reading and visual exploration performance is an equally well-known phenomenon with a long history. Poppelreuter (1917/1990) was the first to report spontaneous oculomotor adaptation in hemianopic patients. Very soon after brain injury, some patients spontaneously adopt eye-movement strategies allowing them to efficiently compensate for their visual-sensory dysfunction. As a consequence, even patients with the most severe visual field defect can regain normal reading and visual exploration performance (Gassel & Williams, 1963; Mackensen, 1962; Meienberg, Zangemeister, Rosenberg, Hoyt, & Stark, 1981; Zangemeister, Oechsner, & Freska, 1995; Zangemeister & Utz, 2002; Zihl, 2000, 2003). Yet, it is still unclear whether efficient spontaneous oculomotor adaptation to visual field loss in reading and visual exploration is task-specific, or whether there is a transfer of adaptation-related improvements between reading and visual exploration. Consequently, our understanding of oculomotor adaptation processes in homonymous visual field loss and thus current rehabilitation practice remains imperfect.

We recently investigated whether and to what extent healthy participants spontaneously adapt to a simulated HH in reading and in visual exploration (Schuett, Kentridge, Zihl, & Heywood, 2009).

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We demonstrated that simulated HH induced the hemianopic reading and visual exploration impairments in healthy participants. Over time, however, all participants showed efficient spontaneous oculomotor adaptation to this pure visual-sensory defect which led to improvements in reading and visual exploration performance. These adaptation processes seemed to occur spontaneously and rapidly, even in the absence of any instruction aimed at improving participants' performance (see also Poppelreuter, 1917/1990). To investigate whether spontaneous oculomotor adaptation is task-specific, or whether there is a transfer of adaptation-related improvements between reading and visual exploration, we conducted a new study that compares the effects of uninstructed reading and visual exploration practice on reading and visual exploration performance with simulated HH in a cross-over design.

2. Methods

2.1. Participants

Twenty-four naïve, healthy participants (8 males, 16 females) participated in this study. Mean age was 19.1 years (S.D.: 1.0) and subjects had on average 12.5 years of education (S.D.: 0.7). All participants were native English speakers with normal or corrected-to-normal vision, had no reading disorders, visual disorders or any other neurological disease or psychiatric condition, and gave their informed consent in accordance with the Declaration of Helsinki and with local ethical committee approval.

2.2. Eye-movement recording and simulating HH

We recorded eye-movements using a pupil and dual Purkinje image video eye-tracker (HS-VET, Cambridge Research Systems). Viewing was binocular and the position of the right eye was sampled at a rate of 250 Hz. We used a sixteen-point grid for equipment calibration which was carried out before each recording session and repeated before each task and block of trials. The Eizo FlexScan F56 monitor (100 Hz, 17", 800 × 600 pixels) used for stimulus presentation subtended 40° horizontally and 32° vertically. Participants' eye level was at the centre of the screen and viewing distance was 38 cm. Their head was fixed by a circular head holder that was firmly attached to a forehead- and chinrest. Ambient room illumination was 1 lx. For controlling stimulus presentation and eye-tracking we used a visual stimulus generator (Cambridge Research Systems) running custom software.

The procedure used to simulate left- and right-sided HH (LHH, RHH) in healthy participants was identical to our previous study, in which we demonstrated that our simulation technique successfully induces reading and visual exploration impairments matching those of hemianopic patients (Schuett et al., 2009). A gaze-contingent visual display completely blanked one side of the screen relative to the current eye position; to simulate LHH or RHH, the side to the left or right of current fixation assumed the colour of the background (see Fig. 1). Based on current eye position (acquired at 2.5 times frame rate), screen update occurred within a single frame (maximum lag: 10 ms). The complete screen area was blanked when saccadic eye shifts landed at positions outside the registration area. Visual field sparing of the simulated HH was 1°, i.e., 1° between foveal eye position and the left or right visual field boundary remained visible (~3 letters in the reading task).

We validated the calibration and accuracy of the simulated visual field boundary before each task and block of trials by assessing the offset between actual and measured eye position using a nine-point grid. If the validation error was smaller than 1° on average and smaller than 0.5° at each point, we repeated the calibration and validation procedure. The accuracy of the simulated visual field boundary was continuously monitored on a control display; in cases of mismatch between actual and measured eye position, we also repeated calibration and validation. Trials with >20% loss of eye-movement data (resulting from lid closures or saccadic eye shifts to positions outside the registration area) were discarded from the analyses (2.3% of trials).

2.3. Assessment of reading performance and eye-movements

For assessing reading and eye-movements during silent text reading we used the same reading task as in our previous study which we demonstrated to be sensitive to adaptation-related changes during uninstructed reading practice with a simulated HH (Schuett et al., 2009). The reading task consisted of four text passages (taken from Oscar Wilde's (1931) "The selfish giant" (pp. 479–483)), each composed of 100 words arranged in eleven, left-aligned lines. Number of characters (including spaces) was similar across text passages (mean: 515.8, S.D.: 10.5). Letter size was 0.8°, letter width 0.3°; spacing between letters was 0.1° and 0.4° between words. About three characters subtended 1° of visual angle. Single lines were separated vertically by 2°. Luminance of the black letters was 0.2 cd/m², against a white background of 27 cd/m². Text passages were of low semantic and syntactic complexity level and consisted of short sentences. The difficulty level was well below the education level of our participants and none of them had read the text before. We previously

demonstrated in a control sample of twenty-five healthy participants that there are no differences among the text passages in any of the parameters describing reading performance and eye-movements (Schuett et al., 2009); the maximal difference (within subjects) in reading time between any two of the four text passages was 2.1 s.

During the assessment of reading performance and eye-movements, we asked participants to read one of the four texts passages silently and only once, with the goal of understanding the text's content. No further instructions were given on how to proceed. For testing comprehension and to confirm that participants had read the text, they were also asked to reiterate its content after reading, which all participants did correctly. Eye-movement recording was started at the onset of text presentation and ended after the participant indicated completion of reading. Reading performance was defined as the time required to read one text passage (reading time). In addition, we analysed the following global temporal and spatial oculomotor parameters for each text: number and mean duration (ms) of fixations, percentage of fixation repetitions (i.e., fixations at previously fixated points), number and mean amplitude (°) of forward (i.e., rightward) saccades, mean amplitude of return-sweep saccades (i.e., the mean first amplitude of eye-movements from the end to the beginning of the next line (°)) and scanpath length (i.e., the sum of all saccadic amplitudes (°)).

2.4. Assessment of visual exploration performance and eye-movements

For assessing visual exploration and eye-movements, we also used the same task as in our previous study which we demonstrated to be sensitive to adaptation-related changes during uninstructed visual exploration practice with a simulated HH (Schuett et al., 2009). The task consisted of five irregular stimulus patterns, each composed of 19, 20 or 21 black dots (diameter: 1°) on a white background presented in randomized order. Dot luminance was 0.2 cd/m², against a white background of 27 cd/m². Dot patterns subtended 18.6° horizontally and 12.4° vertically; minimal spatial separation of any pair of adjacent dots was 6°. Each dot pattern was preceded by the presentation of a fixation spot (0.5°) in the centre of the screen which once fixated, initiated the trial. Participants were asked to silently count the presented dots as accurately and as quickly as possible, and to report the counted number. They were neither informed about the number of dots nor received feedback on their counting performance. Eye-movement recording started with the onset of the dot pattern and ended when the participant reported the number of dots.

Visual exploration performance was defined as exploration time (the time required to perform one trial) and number of errors (all errors committed were omission errors). In addition, we analysed the following global temporal and spatial oculomotor parameters for each trial (five trials in total): number and mean duration (ms) of fixations, mean saccadic amplitude (°) and scanpath length (i.e., the sum of all saccadic amplitudes (°)).

2.5. Reading and visual exploration practice

The reading and visual exploration practice sessions (RP, VP) were identical to those used in our previous study (Schuett et al., 2009). All participants performed one RP and one VP session. During RP, participants were asked to read ten consecutively presented text passages (actual time spent practicing reading: ~15 min.). Text passages were taken from Michael Ende's (1974) "The grey gentlemen", which none of the participants had read before. Characteristics and presentation mode of the texts as well as instructions were identical to those used for the assessment of reading performance. All participants reiterated the content of each text correctly. During VP, patients were asked to perform 30 trials of the visual exploration task used for assessing visual exploration performance (actual time spent practicing visual exploration: ~15 min.). Both practice sessions gave participants the opportunity to learn how to read and explore abstract patterns with a simulated HH without specific advice and instruction to improve performance.

2.6. Procedure

Participants were randomly allocated into two equal groups: Group A ($n = 12$) first performed the reading practice (RP), then the visual exploration practice (VP) session; Group B ($n = 12$) did the converse and first performed the VP, then the RP session in a cross-over design. Half of each group ($n = 6$) performed the two practice sessions with a RHH, the other half with a LHH. Reading and visual exploration performance and eye-movements were assessed before (T_1) and after (T_2) the first practice session, after the second practice session (T_3), and then in a normal viewing condition (N), i.e., without any simulated HH (see Fig. 2). Both the sequence of assessment tasks (performing the reading or visual exploration task first) and that of texts (passages 1–4) used for reading assessment were counterbalanced across participants to eliminate order effects. There were no differences between Group A and B either for demographic variables or for reading and visual exploration performance and oculomotor measures before practice (T_1) and in the normal viewing condition (N) (see Table 1).

In order to disentangle the effects of adaptation to simulated HH from performance changes due to mere practise effects, a new group of six participants (6 females; mean age: 19.3 (S.D.: 1.0); mean years of education: 12.2 years (S.D.: 0.4)) performed the same experimental protocol without any simulated HH (control condition).

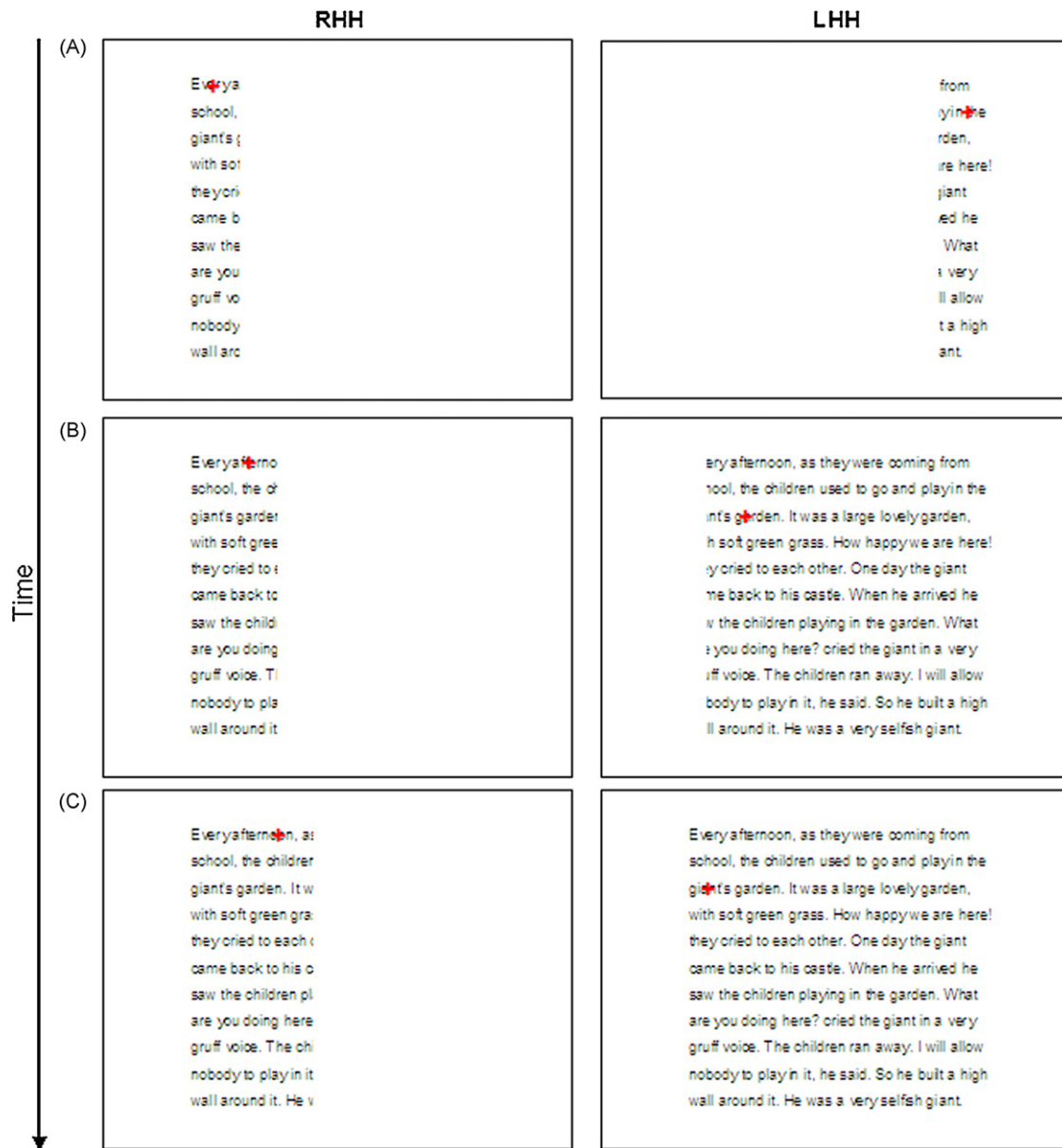


Fig. 1. Schematic illustration of right- and left-sided simulated hemianopia during reading (RHH, LHH); our gaze-contingent display paradigm blanks the side to the right or left of current fixation (visual field sparing: 1°). Potential fixation sequences are illustrated (the red cross indicates potential fixation positions of a participant): RHH: reading the first line (fixating the first word (A)), the beginning (B) and end of the second word (C); LHH: moving the eyes from the end of the second line (A: fixating the last word) to the beginning of the third line (B: fixating the second word due to a too short return-sweep), (C: fixating the first word after a corrective saccade towards the beginning of the line). Figure from Schuett et al. (2009). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

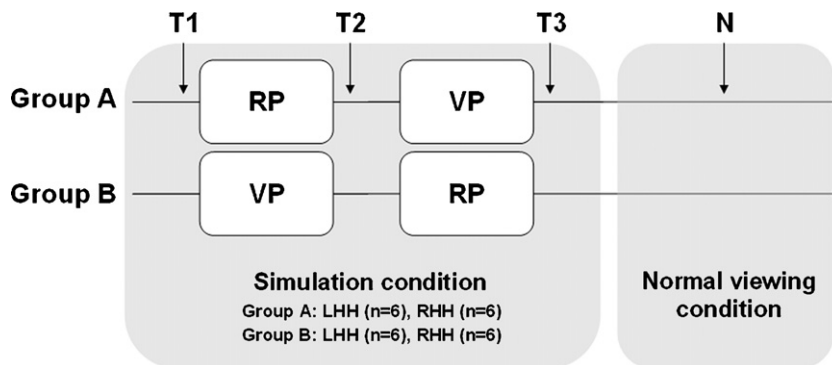


Fig. 2. Illustration of the experimental procedure. Practice sessions in the simulation condition (left- or right-sided hemianopia (LHH, RHH)) were either uninstructed reading practice (RP) or visual exploration practice (VP). T1–T3 indicate the three time points at which we assessed reading and visual exploration with simulated hemianopia; N indicates the time point at which we assessed reading and visual exploration under normal viewing conditions.

Table 1

Demographic details and reading and visual exploration performance with simulated HH before practice (T1) and in the normal viewing condition (N) for Group A and B [mean (S.D., range)].

	Group A (n = 12)	Group B (n = 12)	p
Age (years)	19.2 (1.0, 18–21)	19.0 (1.0, 18–21)	0.748 ^a
Education (years)	12.5 (0.8, 12–14)	12.6 (0.7, 12–14)	0.665 ^a
Sex (female:male)	8:4	8:4	
Side of simulated HH (LHH:RHH)	6:6	6:6	
Reading time (s) ^b			
T1	59.9 (31.3, 16.9–136.3)	65.3 (35.3, 26.4–136.0)	0.708
N	17.5 (3.8, 12.3–23.3)	19.8 (6.1, 12.5–34.9)	0.280
Exploration time (s) ^b			
T1	16.6 (5.4, 8.6–26.4)	14.7 (3.9, 8.3–19.4)	0.329
N	7.0 (1.2, 5.7–10.3)	7.5 (1.5, 5.2–10.9)	0.431
Number of errors			
T1	0.52 (0.55, 0–2.0)	0.55 (0.47, 0–1.4)	0.874
N	0.03 (0.05, 0–0.1)	0.02 (0.04, 0–0.1)	0.368

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

^a Mann–Whitney *U*-tests.

^b There were also no differences for oculomotor reading and visual exploration measures between groups (largest $t_{(22)} = 1.81$, $p = 0.085$).

2.7. Data analysis

The data were analysed by repeated measures ANOVAs (for details on factor variables, see Section 3). Separate analyses were performed for reading and visual exploration performance and oculomotor measures. For the comparisons, either the largest or smallest *F* value is reported. In the control sample, we used Friedman nonparametric analyses of variance to test for overall effects of Time (T1, T2, T3, N) and Wilcoxon tests for post hoc paired comparisons because of the small sample size (two-tailed, $p < 0.05$, Bonferroni-correction).

3. Results

3.1. The effect of simulated HH on reading and visual exploration before practice

We tested whether simulated HH affected reading and visual exploration performance and associated eye-movements before practice (i.e., at T1), and whether there were any order effects reflected in differences between participants who first performed reading practice (Group A) and those who first performed visual exploration practice (Group B). We used simulation condition as a within-subject factor (simulated HH, normal viewing condition) and Group as a between-subject factor (Group A, B). Simulated HH had the expected adverse effect on reading and visual exploration which did not differ between groups (non-significant main and interaction effects: largest $F_{(1,22)} = 3.39$, $p = 0.079$). During reading with simulated HH participants showed significantly longer reading times, a higher number and duration of fixations and refixations, many more and smaller forward saccades and a prolonged scan-path when compared with normal performance (significant effect of simulation condition: smallest $F_{(1,22)} = 23.57$, $p < 0.001$). During visual exploration with simulated HH, participants showed elevated exploration times, made many more errors and the prolonged scan path was characterised by a higher number and duration of fixations (smallest $F_{(1,22)} = 20.18$, $p < 0.001$). However, participants failed to show the expected decrease in return-sweep and exploration saccadic amplitude (smaller $F_{(1,22)} = 2.53$, $p = 0.126$).

3.2. The specificity of practice-related changes in reading and visual exploration with simulated HH

First, we investigated whether the order in which reading and visual exploration practice was carried out had an effect on the changes in reading and visual exploration performance and eye-movements. We used Time as a within-subject factor (before vs.

after the two practice sessions (T1/T3)) and Group as between-subject factor (reading practice first vs. visual exploration practice first (Group A, B)). With a single exception, there were no order effects of whether reading or visual exploration practice occurred first on practice-related changes (non-significant main and interaction effects: largest $F_{(1,22)} = 2.93$, $p = 0.101$). The only exception was that, following the completion of practice, participants who practiced reading first (Group A) showed slightly larger improvements in return-sweep and exploration saccadic amplitude than participants who practiced visual exploration first (Group B) (significant interaction: smaller $F_{(1,22)} = 6.34$, $p = 0.020$).

Secondly, we tested whether there were any carry-over effects from reading practice or visual exploration practice, i.e., whether practicing visual exploration was beneficial (or disadvantageous) to the outcome of subsequent reading practice and *vice versa*. We therefore conducted two repeated measures ANOVAs using Time as a within-subject factor (pre-/post-reading-practice; pre-/post-visual-exploration-practice) and Group as a between-subject factor (Group A, B). We found that the effect of reading practice did not differ between participants who first practiced reading (Group A) and those who received visual exploration practice before practicing reading (Group B) (non-significant interaction effect: largest $F_{(1,22)} = 2.93$, $p = 0.101$). We also found that exploration times and numbers of errors before and after reading practice were significantly larger in participants who had not yet received visual exploration practice (Group A) than those who practiced visual exploration before reading (Group B) (significant main effect of Group, smaller $F_{(1,22)} = 8.30$, $p = 0.009$).

We obtained the same result for visual exploration practice (non-significant main and interaction effects: largest $F_{(1,22)} = 2.19$, $p = 0.153$). We also found that pre- and post-exploration-practice reading times, fixation durations, number of repeated fixations and saccadic amplitudes were significantly larger in participants who had not yet received reading practice (Group B) than in those who had already practiced reading (Group A) (significant main effect of Group, smallest $F_{(1,22)} = 5.47$, $p = 0.029$). The only carry-over effect that was evident was that participants who practiced reading first (Group A) showed a decrease in exploration saccadic amplitude after visual exploration practice whereas those who had not yet received reading practice (Group B) showed an increase in saccadic amplitude (significant interaction: $F_{(1,22)} = 9.23$, $p = 0.006$). In summary there were no order effects or carry-over effects (with a single exception), and the measures for Groups A and B were therefore essentially indistinguishable.

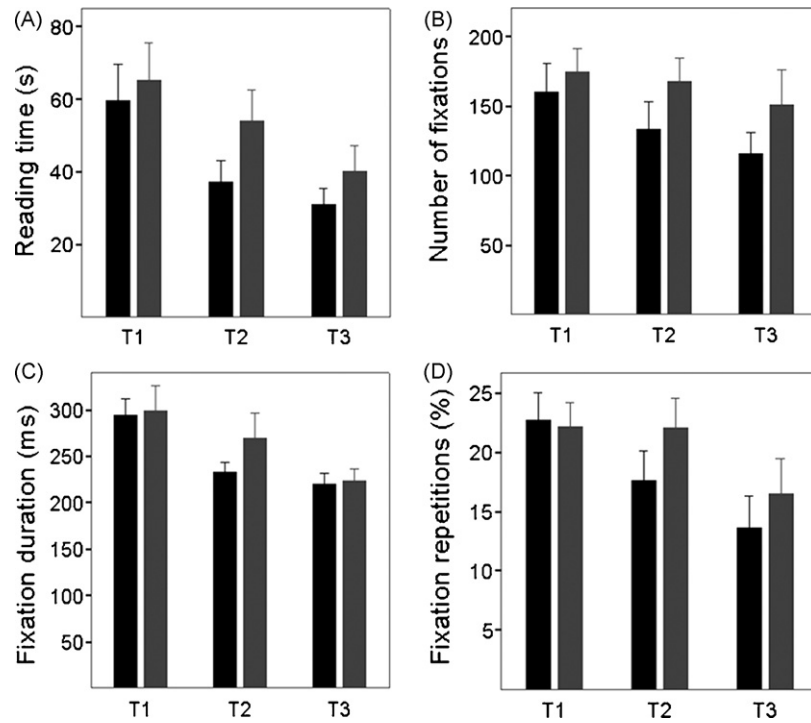


Fig. 3. Mean reading time (s) (A), number of fixations (B), fixation duration (ms) (C), and repeated fixations (%) (D) before practice (T1), after the first (T2) and second practice session (T3). The black bars at T1–T2 (Group A, practice sequence: reading → visual exploration) and the grey bars at T2–T3 (Group B, practice sequence: visual exploration → reading) illustrate the major improvements that were associated with reading practice but not with visual exploration practice (black bars: T2–T3, grey bars: T1–T2).

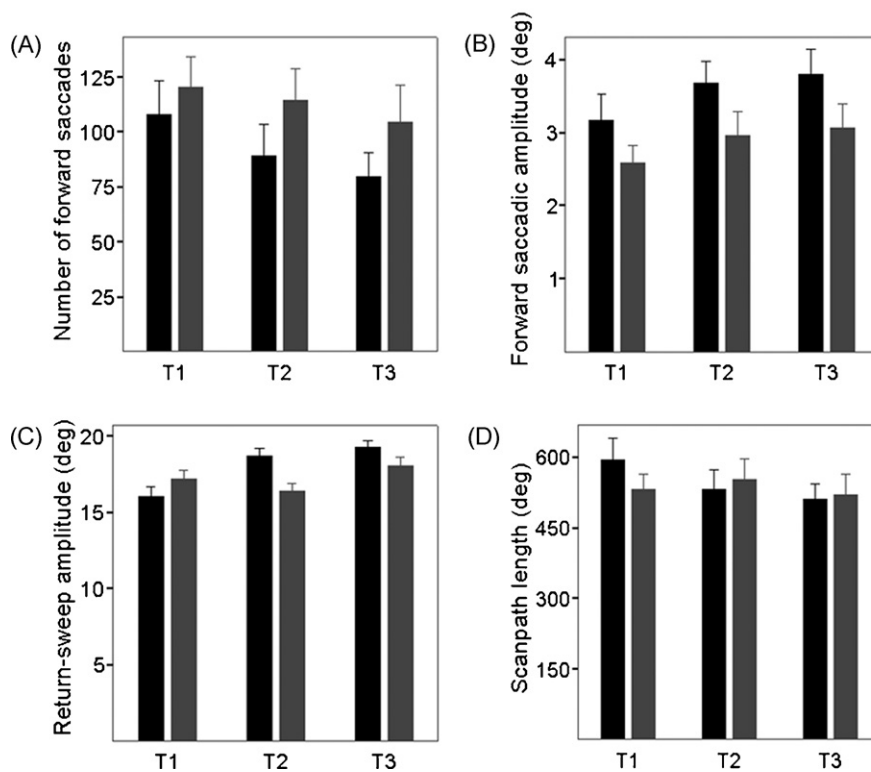


Fig. 4. Mean number (A) and amplitude of forward saccades ($^{\circ}$) (B), return-sweep amplitude ($^{\circ}$) (C), and scanpath length ($^{\circ}$) before practice (T1), after the first (T2) and second practice session (T3). The black bars at T1–T2 (Group A, practice sequence: reading → visual exploration) and the grey bars at T2–T3 (Group B, practice sequence: visual exploration → reading) illustrate the major improvements that were associated with reading practice but not with visual exploration practice (black bars: T2–T3, grey bars: T1–T2).

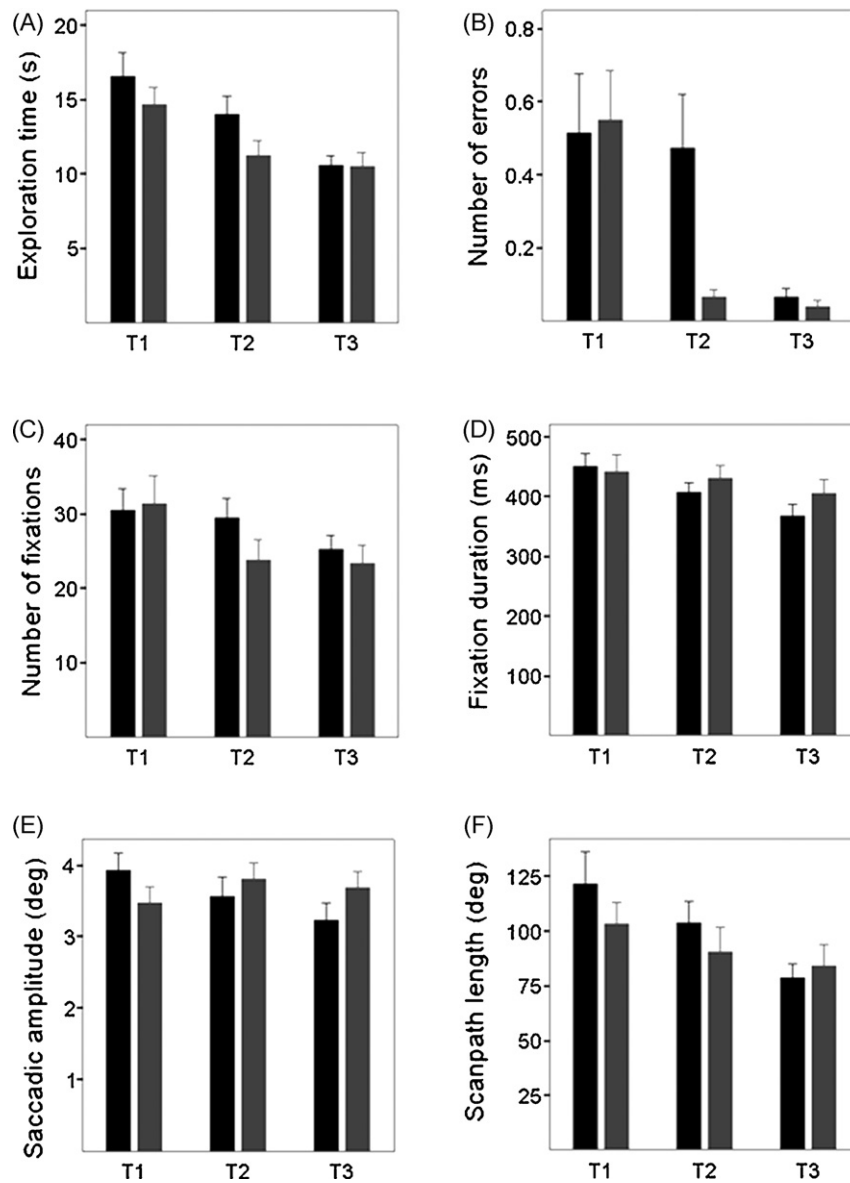


Fig. 5. Mean exploration time (s) (A), number of errors (B), number of fixations (C), fixation duration (ms) (D), saccadic amplitude ($^{\circ}$) (E), and mean scanpath length ($^{\circ}$) (F) before practice (T1), after the first (T2) and second practice session (T3). The grey bars (Group B, practice sequence: visual exploration \rightarrow reading) at T1–T2 and the black bars (Group A, practice sequence: reading \rightarrow visual exploration) at T2–T3 illustrate the major improvements that were associated with visual exploration practice but not with reading practice (grey bars: T2–T3, black bars: T1–T2).

The main result of these three analyses was that performing both reading and visual exploration practice sessions led to significant improvements in all reading and visual exploration performance and oculomotor measures (significant effect of Time (T1/T3): smallest $F_{(1,22)} = 4.67$, $p = 0.042$). More importantly, we found that these improvements were task-specific. Practicing reading and visual exploration with simulated HH led to specific improvements in performance and oculomotor measures of reading (see Figs. 3 and 4) and visual exploration (see Fig. 5), respectively. Reading-practice led to a significant decrease in reading time (significant effect of Time (pre-/post-reading-practice): $F_{(1,22)} = 19.89$, $p < 0.001$) but did not affect visual exploration times and number of errors (larger $F_{(1,22)} = 2.33$, $p = 0.141$). Visual exploration practice, in contrast, induced a significant decrease in exploration time and number of errors (significant effect of Time (pre-/post-visual-exploration-practice): smaller $F_{(1,22)} = 25.18$, $p < 0.001$). Although it also led to a significant decrease in reading time ($F_{(1,22)} = 16.87$, $p < 0.001$), this decrease was very small (-8.7 s) and significantly smaller than

that after reading practice (-18.2 s; $t_{(46)} = 2.05$, $p = 0.045$, two-tailed independent samples t -test).

These findings were mirrored in oculomotor measures. Reading practice led to a significant improvement in all oculomotor reading measures (except scanpath length) but not in oculomotor visual exploration measures. After reading practice, we obtained a significant decrease in number and duration of fixations and forward saccades as well as an increase in the amplitudes of forward saccades and return-sweeps (significant effect of Time (pre-/post-reading-practice): smallest $F_{(1,22)} = 4.41$, $p = 0.047$). Yet, practicing reading had no effect on oculomotor visual exploration measures (largest $F_{(1,22)} = 2.16$, $p = 0.156$), with the exception of a slight decrease in fixation duration ($F_{(1,22)} = 7.21$, $p = 0.014$).

We obtained the converse pattern of results for visual exploration practice. After visual exploration practice, participants showed a significant decrease in the number of fixations and scanpath length during visual exploration (significant effect of Time (pre-/post-visual-exploration-practice): smaller $F_{(1,22)} = 6.90$,

$p=0.015$). Oculomotor reading measures, however, remained unchanged after practicing visual exploration (largest $F_{(1,22)}=2.35$, $p=0.140$), with the exception of slight decreases in the number and duration of fixations and forward saccades during reading (smallest $F_{(1,22)}=6.30$, $p=0.020$). This improvement in fixation duration was significantly much smaller than that induced by reading practice ($t_{(46)}=2.34$, $p=0.023$, two-tailed independent samples t -test).

In addition, we investigated whether there were any differences in performance and practice-related improvements between left- and right-sided simulated HH in reading and visual exploration time, and whether these differences were task-dependent. We used Task (reading, visual exploration) and Time (before and after the two practice sessions (T1/T3)) as within-subject factors and the Side of simulated HH as a between-subject factor (left, right). Consistent with previous reports on HH (e.g., Zihl, 1995a, 2000), we found that reading with a right-sided simulated HH was much more impaired and showed greater improvements after reading practice than reading with a left-sided HH. More importantly, we found that there were no such differences for visual exploration (significant 3-way-interaction: $F_{(1,22)}=6.97$, $p=0.015$). The decrease in reading time after reading practice was significantly larger in right-sided HH (-69.5 s (S.D.: 24.8)) than in left-sided HH (-18.4 s (S.D.: 12.0); $t_{(22)}=6.41$, $p<0.001$). The decrease in exploration time after visual exploration practice, in contrast, was the same for right-sided HH (-6.0 s (S.D.: 4.8)) and left-sided HH (-4.2 s (S.D.: 4.0); $t_{(22)}=1.05$, $p=0.307$) (two-tailed independent samples t -tests).

In summary, our main finding was that the order of reading and visual exploration practice had no effect on the practice-related improvements in reading and visual exploration performance and eye-movements. More importantly, however, we found that these improvements were task-specific.

3.3. The effect of simulated HH on reading and visual exploration after practice

Finally, we tested whether the effects of simulated HH on reading and visual exploration performance and eye-movements we obtained before practice were alleviated by performing reading and visual exploration practice (i.e., at T3), and whether there were any differences between participants who first performed reading practice (Group A) and those who first performed visual exploration practice (Group B). We used Simulation condition as a within-subject factor (simulated HH, normal viewing condition) and Group as a between-subject factor (Group A, B). The effect of simulated HH on reading and visual exploration did not differ between groups (non-significant main and interaction effects: largest $F_{(1,22)}=3.17$, $p=0.089$). Although practicing reading and visual exploration with simulated HH led to significant improvements in reading and visual exploration performance and oculomotor measures, the adverse effect of simulated HH on reading and visual exploration remained after practice (significant effect of Simulation condition: smallest $F_{(1,22)}=6.70$, $p=0.017$). Yet, mean performance differences between the simulated HH and normal viewing condition were much smaller (reading time: 17 s; exploration time: 3.3 s, errors: 0.03) than before practice (reading time: 43.9 s; exploration time: 8.4 s, errors: 0.51).

3.4. Practice effects in the control condition

Analysing the data obtained from our control sample that performed the same experimental protocol without any simulated HH revealed that there were no significant changes in reading or visual exploration performance and eye-movement measures (non-significant effect of Time (T1/T2/T3/N): reading: largest $\chi^2_{(3)}=4.60$, $p=0.218$; visual exploration: largest $\chi^2_{(3)}=7.20$, $p=0.060$). Although there was a significant effect for number of fixations in reading ($\chi^2_{(3)}=10.16$, $p=0.010$), no difference between

any two of the four time points was significant ($Z=-2.21$, $p=0.124$). Moreover, the obtained decrease was very small (-10%) and they were not associated with improvements in reading and visual exploration performance measures since these remained unchanged.

4. Discussion

The purpose of our study was to determine the specificity of efficient oculomotor adaptation to visual field loss in reading and visual exploration. We therefore investigated whether spontaneous oculomotor adaptation to simulated HH during reading practice and visual exploration practice is task-specific, or whether there is a transfer of practice-related improvements between reading and visual exploration.

Our observation that practice-related improvements in reading and visual exploration performance were accompanied by changes of the respective oculomotor measures indicates efficient spontaneous oculomotor adaptation to simulated HH. Even in the absence of any instruction aimed at improving performance, participants spontaneously adapted to simulated HH by developing efficient oculomotor compensation strategies that alleviated their hemianopic reading and visual exploration impairments. It is important to note that these improvements cannot be explained by increases in visual field sparing during the experimental sessions since the accuracy of the simulated visual field border was continuously monitored. Moreover, they can neither be attributed to mere practice effects since performing the RP and VP sessions under normal viewing conditions was not associated with any performance or oculomotor changes. In addition, there was no evidence of a speed-accuracy trade-off after practice, neither for reading nor for visual exploration performance; participants reiterated the content of each text equally correctly before and after practice and the number of errors during visual exploration decreased significantly.

This finding replicates our own recent study on spontaneous oculomotor adaptation in healthy participants with simulated HH (Schuett et al., 2009) and is consistent with previous reports that investigated adaptation processes in artificial visual field loss during reading (Bernard, Scherlen, & Castet, 2007; Fornos, Sommerhalder, Rappaz, Pelizzone, & Safran, 2006; Sommerhalder et al., 2003, 2004) or visual exploration (Zangemeister & Oechsner, 1999; Zangemeister & Utz, 2002).

Yet, more importantly, this study showed that efficient spontaneous oculomotor adaptation to visual field loss is highly specific and task-dependent. Our results demonstrate that uninstructed RP with simulated HH led to significant improvements in reading performance and associated eye-movements but had no effect on visual exploration; likewise, while VP could significantly improve visual exploration performance and associated eye-movements, it had no effect on reading. This lack of transfer of practice-related changes of oculomotor measures and performance improvements between reading and visual exploration suggests that both visuo-motor abilities require specific oculomotor adaptation processes for their improvement. Neither efficient oculomotor adaptation to visual field loss in reading nor efficient adaptation in visual exploration alone is sufficient to improve both abilities. Efficient spontaneous oculomotor adaptation to a pure visual-sensory dysfunction is task-specific. Our finding that the effect of the side of simulated HH on the resulting impairment and practice-related improvement was also task-dependent confirms this assumption and is consistent with previous reports on hemianopic patients (Zihl, 1995a, 2000).

Although reading and visual exploration are both visuo-motor abilities, they are special applications of the visual, attentional and

oculomotor systems. The visually and linguistically structured environment as well as the visual material involved in reading imposes a notably different visual sampling strategy than a complex and less systematic scene. Moreover, the cognitive demands differ quite substantially between reading and visual exploration. In contrast to visual exploration, reading requires not only visual, attentional and oculomotor but also linguistic processes; it is the process of understanding written language (Liversedge & Findlay, 2000; Rayner, 1998). Thus, visual information sampling and processing in reading serve quite different purposes than those in visual exploration and are therefore task-specific.

The finding that visual field loss can be successfully alleviated by oculomotor adaptation shows the functional plasticity of the visual, attentional and oculomotor processes involved in reading and visual exploration (Schuett et al., 2008a). Yet, specificity rather than generality in transfer of adaptation-related oculomotor changes and performance improvements between both abilities suggests that the functional plasticity of these processes is task-dependent. Task-specific limitations in neural and cognitive plasticity across the adult lifespan support this assumption; age-associated reductions in cognitive plasticity seem to be task-specific (Jones et al., 2006). Further evidence stems from mirror reading. The acquisition of mirror reading skill requires specific and systematic practice (Ofen-Noy, Dudai, & Karni, 2003) and seems to be associated with gray matter increase in task-specific processing areas (Ilg et al., 2008). Moreover, our finding may indicate task-specificity in the functional specialisation of the (cortical) oculomotor system (Alahyane et al., 2007).

Task-specificity in spontaneous oculomotor adaptation explains the double dissociation between spontaneous oculomotor adaptation to visual field loss in reading and visual exploration and consequently that of the hemianopic reading and visual exploration impairments (Zihl, 2000), which has been unclear thus far. Analyses of the anatomical basis of these impairments further support our assumption. If injury to the postchiasmatic visual pathway is accompanied by additional injury to the occipital white matter comprising subcortical–cortical reciprocal connections and/or to the posterior thalamus, hemianopic patients do not show efficient spontaneous oculomotor adaptation to visual field loss in reading and their ability to read remains severely impaired (Zihl, 1995a). The hemianopic visual exploration impairment emerges if the additional injury involves the ipsilateral occipito-parietal cortex and/or posterior thalamus; these patients do not spontaneously adapt to their visual field loss in visual exploration (Zihl, 1995b). These structures are assumed to be part of the distinctive though overlapping networks subserving the control of visual and oculomotor processes in reading (Schuett et al., 2008a) or visual exploration (Mort & Kennard, 2003), respectively. Yet, they may also play a significant role in spontaneous oculomotor adaptation to visual field loss in the respective visuo-motor abilities.

Efficient spontaneous oculomotor adaptation and consequent improvements in reading and visual exploration seem to occur only if brain injury is restricted to the postchiasmatic visual pathway. If injury to the postchiasmatic visual pathway is accompanied by additional lesions affecting the occipital white matter, occipitoparietal structures, and/or the posterior thalamus, hemianopic patients either show insufficient or no spontaneous oculomotor adaptation (Zihl, 1995a, 1995b). It is important to note, however, that there are rare reports of hemianopic patients with confined postchiasmatic lesions who nevertheless do not spontaneously compensate for their visual field defect in reading (Upton, Hodgson, Plant, Wise, & Leff, 2003). The high frequency of combined striate/extrastriate lesions in patients with homonymous visual field loss (Hebel & von Cramon, 1987) may explain why efficient spontaneous oculomotor adaptation to visual field loss occurs rarely. Moreover, it is consistent with the observation that patients either start compensating

for their visual field defect soon after brain injury or never regain normal reading and visual exploration performance, at least not without systematic treatment (Zihl, 1995a, 1995b, 2000).

In current clinical practice, hemianopic patients with reading and visual exploration impairments receive two distinct compensatory treatments for improving their impaired reading and visual exploration performance. Improving reading in hemianopic patients seems to require practising rather smaller, very precise, systematic and regular horizontal saccadic eye-movements with single words (Zihl, 2000). Yet, we recently demonstrated that the treatment effect of systematic oculomotor reading training does not depend on the linguistic but on the visual properties of words, indicating a transfer of treatment-related oculomotor adaptation from processing visual symbols to reading words, sentences and text passages. This transfer was, however, limited since the treatment effect did not generalise to visual exploration (Schuett, Heywood, Kentridge, & Zihl, 2008b). Improving the hemianopic visual exploration impairment, in contrast, requires practicing the use of large saccadic eye-movements to enlarge the field of view as well as practicing more systematic and spatially organised scanning strategies. Treatment-related oculomotor adaptation seems to transfer from processing abstract visual stimulus arrays and visual search displays during training sessions to natural scene viewing, orienting and navigating (Zihl, 2000). Recent evidence suggests, however, that it does not transfer to text reading (Spitzyna et al., 2007). Although a compensatory visual exploration training involving audio-visual stimulation was found to improve reading in hemianopic patients, it is important to note that the evaluation of reading improvement was based only on single-word reading accuracy (Bolognini, Rasi, Coccia, & Ládavas, 2005), which is not sufficient for an ecologically valid assessment of hemianopic dyslexia and related treatment effects (Schuett et al., 2008a).

Our finding of specificity rather than generality in transfer of adaptation-related improvements between reading and visual exploration is consistent with current rehabilitation practice and may suggest that not only spontaneous but also treatment-related oculomotor adaptation to visual field loss is task-specific. Moreover, we found that the cumulative effect of practicing reading and visual exploration with simulated HH did not differ between participants who first practiced reading and those who first practiced visual exploration. Thus, one may speculate that the treatment sequence in the rehabilitation of the hemianopic reading and visual exploration impairments may not determine the overall treatment outcome.

However, it requires cross-over rehabilitation studies to determine whether these hemianopic impairments are best treated using specific methods and whether there is an optimal treatment sequence. Although the oculomotor changes and performance improvements that occurred spontaneously in our healthy participants may be similar to those of hemianopic patients who receive systematic treatment to reinforce these adaptation processes (Zihl, 1995a, 1995b, 2000), our evidence was obtained on the basis of relatively young and well-educated healthy participants. Yet, the majority of hemianopic patients are over the age of 55 (Zihl, 2000). Moreover, since neural and cognitive plasticity changes across the lifespan (Burke & Barnes, 2006; Craik, 2006; Hedden & Gabrieli, 2004; Reuter-Lorenz, 2002; Sowell et al., 2003), age or age-related processes may play a significant role in oculomotor adaptation to visual field loss and therefore (co-)determine not only patients' functional impairments but also the amount of treatment required and the overall rehabilitation outcome. Yet, apart from a single report on the effect of age on spontaneous oculomotor adaptation to simulated and real HH in visual exploration (Tant et al., 2002), it remains to be investigated whether and to what extent age can influence spontaneous and treatment-related oculomotor adaptation to visual field loss.

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