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Are hemianopic reading and visual exploration impairments visually elicited? New insights from eye movements in simulated hemianopia

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ABSTRACT

Hemianopic reading and visual exploration impairments are well-known clinical phenomena. Yet, it is unclear whether they are primarily caused by the hemianopic visual field defect itself or by additional brain injury preventing efficient spontaneous oculomotor adaptation. To establish the extent to which these impairments are visually elicited we simulated unilateral homonymous hemianopia in healthy participants, using a gaze-contingent display paradigm, and investigated its effect on reading and visual exploration. We demonstrate that simulated hemianopia induces the reading and visual exploration impairments of hemianopic patients. Over time, however, all participants showed efficient spontaneous oculomotor adaptation to the visual-sensory loss which improved their reading and visual exploration performance. Our results suggest that the hemianopic visual field defect is a major component of the chronic impairments of reading and visual and exploration found in hemianopic patients although it may not be their sole cause.

1. Introduction

Unilateral homonymous hemianopia (HH) is a common functional impairment after brain damage. It is a visual field disorder caused by injury to the postchiasmatic visual pathway, which leads to loss of vision in both monocular hemifields contralateral to the side of brain injury. Posterior cerebral artery infarction is its most frequent aetiology and seldom restricted to striate cortex (Zhang, Kedar, Lynn, Newman, & Biousse, 2006; Zihl, 2000). Sufficient spontaneous recovery of the visual field occurs rarely (Zihl & Kennard, 1996). The majority of hemianopic patients show persistent and severe impairments of reading (hemianopic dyslexia) and visual exploration (Zihl, 2000, 2003). Hemianopic reading and visual exploration impairments are well-established clinical phenomena with a long history (for early descriptions, see Mauthner, 1881; Pfeifer, 1919; Poppelreuter, 1917/1990; Wilbrand, 1907).

Hemianopic dyslexia is an acquired reading disorder which is frequently associated with HH affecting parafoveal and/or foveal vision (for a comprehensive review, see Schuett, Heywood, Kentridge, & Zihl, 2008a). Difficulties in word identification and reading eye-movement control impair the ability to read text quickly and efficiently despite intact language functions. The main behavioural feature of hemianopic dyslexia is very slow reading that is characterised by visual omission and guessing errors as well as severe alterations in the pattern of reading eye-movements. Patients show an increased number and duration of fixations and repeated fixations as well as much smaller saccadic eye-movements (e.g. Leff et al., 2000; McDonald, Spitzyna, Shillcock, Wise, & Leff, 2006; Schuett, Heywood, Kentridge, & Zihl, 2008b; Spitzyna et al., 2007; Trauzettel-Klosinski & Brendler, 1998; Zihl, 1995a, 2000). Hemianopic patients also typically show a severe impairment of visual exploration. It disturbs the ability to gain a complete overview of the visual surroundings and leads to difficulties in detecting and locating objects, avoiding obstacles and in orienting and navigating in unfamiliar surroundings. The hemianopic visual exploration impairment is distinguished by considerably increased visual search and scanning times, as well as target omissions, longer and unsystematic scanpaths, a higher number of fixations, smaller saccades and, at least in part, longer fixation durations (e.g. Mort & Kennard, 2003; Pambakian et al., 2000; Tant, Cornelissen, Kooijman, & Brouwer, 2002; Zihl, 1995b, 1999, 2000).

Although a high degree of consensus about the characteristics of the hemianopic reading and visual exploration impairments has been reached, the causes of these impairments are, however, still unknown. It is a matter of debate whether hemianopic reading and visual exploration impairments are consequences of the

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hemianopic visual field defect itself, or whether they are caused by additional brain injury preventing efficient spontaneous oculomotor adaptation. Moreover, the dissociability of hemianopic reading and visual exploration impairments (Zihl, 2000) raises the question as to whether these impairments are caused by a common underlying mechanism. The visual origin of hemianopic dyslexia is supported by studies that investigate the significance of parafoveal vision for reading in normal readers; occluding the parafoveal visual field by paracentral masks induces behavioural changes in reading that correspond with the hemianopic reading impairment (Cummings & Rubin, 1992; Fine & Rubin, 1999a; Ikeda & Saida, 1978; McConkie & Rayner, 1975, 1976; Rayner & Bertera, 1979; Rayner, Inhoff, Morrison, Sowiaczek, & Bertera, 1981; Rayner, Liversedge, & White, 2006). Studies investigating the effects of a simulated hemianopic visual field defect on visual exploration in healthy individuals provide additional evidence that the visual exploration impairment associated with HH may be a consequence of the visual field loss rather than of additional brain damage (Tant et al., 2002; Zangemeister & Oechsner, 1999; Zangemeister & Utz, 2002). Yet, observations of patients showing normal reading and visual exploration performance despite visual field loss indicate that the hemianopic visual field defect may be a necessary but not sufficient condition that causes the hemianopic reading and visual exploration impairments. Very soon after brain injury, these patients seem to spontaneously adopt eye-movement strategies which allow them to efficiently compensate for their visual-sensory dysfunction (Gassel & Williams, 1963; Zihl, 2000, 2003). It has therefore been suggested that additional lesions preventing efficient spontaneous oculomotor adaptation may be required for the hemianopic reading and visual exploration impairments to persist (Zihl, 1995a, 1995b).

As long as it is unclear whether the hemianopic reading and visual exploration impairments are caused by the visual field loss itself or by additional brain injury, and whether they are caused by a common underlying mechanism, our understanding of these functional impairments remains incomplete. Consequently, current practice of assessment and rehabilitation of visual field loss after brain injury is imperfect. Thus, investigating the causes of these functional impairments is both of theoretical but also of high clinical–practical relevance. The purpose of the reported experiments therefore was to identify the visual components that may constitute the hemianopic reading and visual exploration impairment as well as to establish the extent to which these impairments are visually elicited. We used a gaze-contingent display paradigm (McConkie & Rayner, 1975; Rayner & Bertera, 1979) to simulate HH in healthy participants, which allows us to study the behavioural changes associated with the hemianopic visual field defect that are not caused by brain injury. In Experiment 1, we investigated the effects of simulated HH on reading and visual exploration. In addition, we examined the effects of simulated HH on saccadic accuracy which is regarded as an indicator of efficiency of visual exploration and is often impaired in hemianopic patients (Meienberg, Zangemeister, Rosenberg, Hoyt, & Stark, 1981; Zihl, 2000). In Experiment 2, we investigated whether and to what extent healthy participants spontaneously adapt to simulated HH in reading (Experiment 2a) and in visual exploration (Experiment 2b).

2. Experiment 1: the effects of simulated HH on reading, visual exploration, and saccadic accuracy

2.1. Methods

2.1.1. Participants

For each of the three experiments (Experiments 1, 2a and 2b), we tested a new group of naïve, healthy participants with normal or corrected-to-normal vision. They were native English speakers and 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. In Experiment 1, we tested 17 participants (8 males, 9 females; mean age: 38.7 years (S.D.: 11.6); years of education: 11.2 years (S.D.: 3.5)) for investigating the effects of simulated HH on reading, visual exploration, and saccadic accuracy.

2.1.2. Eye-movement recording and simulating HH

Eye-movements were recorded using a pupil and dual Purkinje image video eye-tracker (HS-VET, Cambridge Research Systems) with a sampling frequency of 250 Hz and a spatial resolution of 0.05° of visual angle. Since previous research on reading and visual exploration in hemianopic patients is based on monocular eye-movement recordings during binocular viewing (e.g. Leff et al., 2000; McDonald et al., 2006; Mort & Kennard, 2003; Pambakian et al., 2000; Schuett et al., 2008b; Spitzyna et al., 2007; Tant et al., 2002; Trauzettel-Klosinski & Brendler, 1998; Zihl, 1995a, 1995b, 1999, 2000), we sampled the position of the right eye under binocular viewing conditions. Prior to each recording session, the equipment was calibrated using a 16-point grid; calibration was repeated before each task and block of trials. Stimuli were presented on an Eizo FlexScan F56 monitor (100 Hz, 17″, 800 × 600 pixels) which subtended 40° horizontally and 32° vertically. Participants were seated comfortably at a viewing distance of 38 cm with the centre of the screen at eye level. To prevent head movements, each participant's head was tightly strapped to a circular head holder that was firmly attached to a forehead- and chinrest. Ambient room illumination was 1 lx. Stimulus presentation and eye-tracking was controlled by a visual stimulus generator (Cambridge Research Systems) running custom software.

Left- and right-sided HH (LHH, RHH) was simulated with a gaze-contingent visual display paradigm which completely blanks one side of the screen relative to the current eye position, i.e. the side to the left or right of current fixation (to simulate LHH or RHH respectively) assumes the colour of the background (Fig. 1). In patients with HH after unilateral postchiasmatic damage, the foveal visual field (±0.5–1.0° to the left or right of fixation) is spared and macular sparing (±1–5°) is infrequent (Gray, Galetta, Siegal, & Schatz, 1997; Reinhard & Trauzettel-Klosinski, 2003; Zihl, 1989, 2000). We therefore chose a visual field sparing of 1° for our simulated HH, i.e. between each participant's foveal eye position and the left or right border of the simulated HH 1° of the visual field (~3 letters in the reading task) remained visible. When saccadic eye shifts landed at positions outside the registration area, the complete screen area was blanked. An update of the entire display occurred within a single frame (maximum lag: 10 ms) based on current eye position (acquired at 2.5 times frame rate). In developing our simulated HH paradigm, we also considered it crucial to consult patients with HH after brain injury and discuss their subjective experience of the visual field loss. In order to match patient's descriptions of their subjective experience, we created a simulated visual field defect that conveys no visual information (blank defect with the colour of the background) rather than using textured (e.g. Rayner et al., 1981) or black masks on white background (e.g. Fine & Rubin, 1999a). This is also in line with a recent finding suggesting that a textured mask obliterating visual information to the right of fixation in reading attracts attention and leads to an attentional shift to the mask (Rayner et al., 2006), which is not the case in cerebral visual field defects.

Prior to each task and block of trials, calibration and the accuracy of the simulated visual field border were validated; we used a nine-point grid validation to assess the offset between actual and measured gaze location. Calibration and validation were repeated if the validation error was greater than 1° on average or greater than 0.5° at each point. During trials, the match between actual

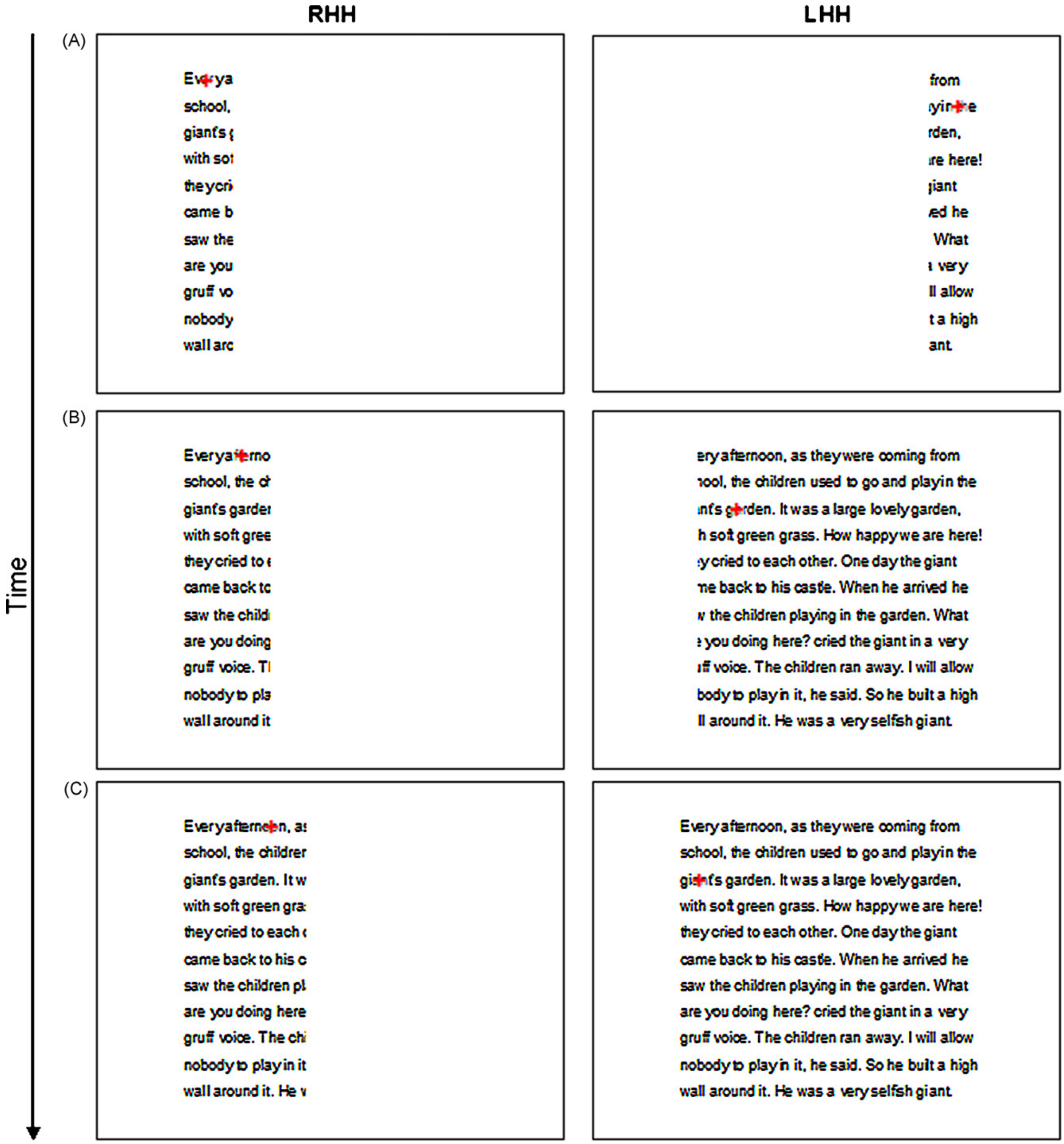

Fig. 1. Schematic illustration of right- and left-sided simulated hemianopia during reading (RHH, LHH); our gaze-contingent display paradigm blanks the side to the right or left of current fixation (visual field sparing: 1°). Potential fixation sequences are illustrated (the red cross indicates potential 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 and (C) fixating the first word after a corrective saccade towards the beginning of the line).

and measured gaze location was continuously monitored on a control display; in cases of mismatch, calibration and validation were repeated. Trials with >20% loss of eye-movement data (as a result of lid closures or saccadic eye shifts to positions outside the registration area) were not included in the analysis.

2.1.3. Assessment of reading and eye-movements

Materials for assessing reading and eye-movements during silent text reading consisted of six text passages taken from Oscar Wilde's (1931) "The selfish giant" (pp. 479–483). None of the participants had read this fairy tale before. Each text consisted of 100 words arranged in eleven, left-aligned lines. Number of characters (including spaces) was similar across the selected text passages (mean: 507.7, S.D.: 15.0). 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 $\mathrm{Cd/m^2}$, against a white background of 27 $\mathrm{Cd/m^2}$. The texts were characterised by short sentences with a low semantic and syntactic complexity level; we assumed that the difficulty level of the texts was well below the education level of our participants.

There were no differences among the selected six text passages in any of the parameters describing reading performance and eye-movements, as assessed in a control sample of 25 participants (12 males, 13 females; mean age: 19.0 years (S.D.: 1.2); years of education: 12.4 (S.D.: 0.8)). There was no significant effect of text passage (6-level within-subject factor) for reading time ($F_{(5,144)} = 0.59$, $p = 0.707$) or for any oculomotor reading measures (number and duration of fixations and repeated fixations, mean amplitude of forward and return-sweep saccades, scanpath length) (largest $F_{(5,144)} = 2.03$, $p = 0.078$; ANOVA); the maximal difference in reading time between any two of the six text passages was 2.3 s.

For assessing reading performance and eye-movements, participants were asked to read one of these 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 started with the onset of text presentation and ended after the participant indicated completion of reading. A similar reading test (in German) has been found to be sensitive to changes in reading performance and related oculomotor measures during treatment of hemianopic dyslexia (Zihl, 1995a, 2000).

Reading performance was defined as the time required to read one text passage (reading time), i.e. time elapsed between reading the first and the last word of the text. For the assessment of reading eye-movements, we analysed the following global temporal and spatial oculomotor parameters: 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 (°)).

2.1.4. *Assessment of visual exploration and eye-movements*

For assessing visual exploration and eye-movements, irregular stimulus patterns consisting of 19, 20 or 21 black dots (diameter: 1°) on a white background were presented in randomized order. This task has been found to be sensitive to changes in oculomotor visual exploration measures during treatment in patients with HH (Zihl, 1995b, 1999, 2000). Dot luminance was 0.2 Cd/m^2, against a white background of 27 Cd/m^2. Dot patterns were created by randomly assigning the dots to any of 24 possible positions in a rectangular imaginary 6 × 4 grid (subtending 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°) displayed 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 their number. This test is similar to the dot cancellation test (Lezak, Howieson, & Loring, 2004) but did not include feedback on which dots had already been counted. No instruction was given on the number of dots or how to proceed with counting or search; participants received no feedback on the number of counted dots. Eye-movement recording started with the onset of the dot pattern and was ended when the participant indicated completion of dot counting and reported their number.

Visual exploration performance was defined as visual exploration time (the time required to perform one trial) and number of errors (all errors committed were omission errors). For the assessment of visual exploration eye-movements, we analysed the following global temporal and spatial oculomotor parameters: number and mean duration (ms) of fixations, mean saccadic amplitude (°) and scanpath length (i.e. the sum of all saccadic amplitudes (°)). In addition, we performed directional and hemispace analyses (Tant et al., 2002; Zihl, 1995b). We analysed number and mean amplitude (°) of left- and rightward saccades (directional analysis) as well as number and mean duration (ms) of fixations spent in left and right hemispace, which is defined with respect to the centre of the screen (hemispace analysis).

2.1.5. *Assessment of saccadic accuracy*

For assessing the accuracy of intentional saccadic eye-movements to visual targets, we used two simultaneously presented black dots (diameter: 1°), one of which was presented 10° to the left, the other 10° to the right of the screen's centre in the horizontal plane (distance between dots: 20°). Dot luminance was 0.2 Cd/m^2 against a white background of 27 Cd/m^2. The simultaneous presentation of the two dots was preceded by a fixation dot (0.5°) in the centre of the screen. Participants were asked to alternate their gaze back and forth between the two simultaneously presented dots as accurately as possible; they were informed that the target-dot located in their blind hemifield is presented at the same distance from the centre in the horizontal plane as the target-dot located in their seeing hemifield (Zihl, 2000; Zihl & Hebel, 1997). Eye-movement recording started with the onset of the display and ended when the participant had performed at least 10 saccadic eye shifts.

Saccadic accuracy was defined as mean saccadic gain, i.e. the quotient of initial saccadic amplitude and target distance for left- and rightward saccades. A saccadic gain of 1 indicates perfect correspondence between target and eye position. Under- or overshooting of the target is referred to as saccadic dysmetria, i.e. hypo- or hypermetria, respectively. Accuracy of each saccade was considered as normal when saccadic gain was between 0.88 and 1.06, hypometric when the gain was <0.88 and as hypermetric when the gain was >1.06. These cut-off values were derived from the average gain ± 1 S.D. of participants' left- and rightward initial saccades in the non-simulation condition (mean: 0.97°, S.D.: 0.09) (Zihl, 2000). For each participant, we analysed the mean amplitude (°) and saccadic gain of initial left- and rightward saccades as well as frequency of normal, hypo- and hypermetric initial left- and rightward saccades.

2.1.6. *Procedure*

All participants performed each task, i.e. reading (1 text passage out of 3), visual exploration (10 trials) and saccadic accuracy (3 trials) with simulated LHH, RHH and in a normal viewing condition, i.e. without any simulated HH (*N*). Task performance in the normal viewing condition as well as reports on each participant's subjective experience with simulated HH was obtained at the end of the experiment. The sequence of simulation conditions (starting with LHH or RHH), tasks and text passages used for reading assessment were counterbalanced across participants to eliminate order effects. To avoid adaptation and practice effects, the same simulation condition (LHH or RHH) was never imposed in succession and the same task was never performed consecutively; before performing the same task again in a different simulation condition, the two other tasks had to be performed.

2.1.7. *Data analysis*

For testing the effects of simulated HH on reading, visual exploration and saccadic accuracy, we performed a repeated measures ANOVA with simulation condition (LHH, RHH, *N*) as a within-subject factor for each task. For hemispace and directional analyses of the visual exploration data, we performed repeated measures ANOVAs with simulation condition (LHH, RHH, *N*) and space/direction (left, right) as a within-subject factors. Where sphericity assumptions were violated as assessed by Mauchly's *W*

Table 1
Reading performance and related oculomotor parameters in left- and right-sided simulated hemianopia (LHH, RHH) and in the normal viewing condition (*N*) [mean (S.D., range)].

	LHH	RHH	*N*	*N*–LHH	*N*–RHH	LHH–RHH
Reading time (s)	34.1 (15.2, 14.6–79.4)	57.7 (23.9, 25.5–115.3.0)	19.0 (4.2, 14.1–29.0)	*	*	*
Total fixations						
Number	111.1 (32.7, 57.0–173.0)	155.1 (36.5, 73.0–233.0)	79.8 (16.5, 54.0–122.0)	*	*	*
Duration (ms)	244 (58.6, 181–401)	316 (105.4, 192–631)	180 (17.4, 153–225)	*	*	*
Repeated fixations (%)	18.5 (9.5, 3.5–38.2)	20.3 (10.0, 3.1–40.4)	12.3 (5.5, 4.6–25.4)	*	*	n.s.
Forward saccades						
Number	70.4 (15.8, 43.0–108.0)	101.5 (30.0, 47.0–154.0)	53.1 (9.6, 39.0–71.0)	*	*	*
Amplitude (°)	3.8 (0.6, 3.0–5.1)	3.3 (1.3, 1.9–5.4)	4.3 (0.6, 3.3–5.4)	*	*	$p = 0.031$
Return-sweep amplitude (°)	15.8 (1.9, 11.8–19.1)	15.4 (2.4, 10.0–18.5)	17.2 (1.4, 14.7–19.7)	*	*	n.s.
Scanpath length (°)	529.0 (84.3, 401.6–667.9)	604.2 (132.1, 437.2–860.3)	457.0 (50.2, 373.6–544.8)	*	*	$p = 0.028$

Statistical comparisons were made between LHH, RHH, and *N* (one-tailed dependent samples *t*-tests).
n.s. indicates non-significant comparisons.
* $p < 0.017$ (α_{corr}); *p*-values are given for marginally significant results.

test, we applied the Greenhouse–Geisser correction to the degrees of freedom. Post hoc paired comparisons between simulation conditions and space/directions were performed using repeated measures *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. 4.3% of trials were excluded from the visual exploration data analyses.

2.2. Results

2.2.1. The effect of simulated HH on reading

Reading and eye-movements of healthy participants were adversely affected by simulated HH (Table 1), as indicated by a significant effect of simulation condition for reading time and all oculomotor parameters (smallest $F_{(1.2,19.3)} = 4.49$, $p = 0.041$). Reading with simulated LHH or RHH was characterised by significantly longer reading times, a higher number and duration of fixations and refixations, many more and smaller forward saccades, a smaller return-sweep and a prolonged scanpath when compared with normal performance. Reading performance also differed significantly between LHH and RHH, except for the rate of fixation repetitions and the return-sweep amplitude. Reading with RHH was much more impaired than reading with LHH.

2.2.2. The effect of simulated HH on visual exploration

Simulated HH also had a detrimental effect on visual exploration and eye-movements of healthy participants (Table 2), as indicated by a significant effect of simulation condition for visual exploration time, number of errors, and for the majority of oculomotor parameters (smallest $F_{(2,32)} = 3.85$, $p = 0.032$). Visual exploration with simulated LHH and RHH was characterised by significantly longer visual exploration times, more errors, a higher number and duration of fixations, smaller saccades (significant for RHH only), and a prolonged scanpath. There were no significant differences between LHH and RHH for these performance measures.

Although we did not obtain a significant effect of simulation condition for saccadic amplitude, number and amplitude of left- and rightward saccades and for duration of right-hemispace fixations (largest $F_{(1.3,20.6)} = 3.65$, $p = 0.061$), hemispace and directional analyses revealed a significant interaction between simulation

Table 2
Visual exploration performance and related oculomotor parameters in left- and right-sided simulated hemianopia (LHH, RHH) and in the normal viewing condition (*N*) [mean (S.D., range)].

	LHH	RHH	*N*	*N*–LHH	*N*–RHH	LHH–RHH
Visual exploration time (s)	15.5 (5.3, 8.5–28.8)	18.6 (15.6, 10.7–74.5)	8.7 (1.8, 5.4–12.4)	*	*	n.s.
Number of errors	0.7 (0.7, 0–2.3)	0.8 (0.6, 0–2.4)	0.1 (0.1, 0–0.3)	*	*	n.s.
Total fixations						
Number	27.3 (9.4, 16.1–46.7)	31.8 (17.7, 17.5–76.2)	18.7 (3.8, 14.1–26.0)	*	*	n.s.
Duration (ms)	452 (70.4, 319–591)	439 (114.3, 267–752)	356 (90.3, 234–609)	*	*	n.s.
Saccadic amplitude (°)	4.2 (0.9, 2.7–7.1)	4.2 (0.9, 2.3–6.5)	4.5 (0.6, 3.1–5.7)	n.s.	*	n.s.
Scanpath length (°)	118.6 (58.7, 54.1–293.5)	128.4 (67.6, 60.7–321.7)	85.2 23.8, 45.2–120.3)	*	*	n.s.
Right hemispace fixations						
Number	12.7 (5.3, 6.8–22.7)	18.3 (12.0, 10.0–50.1)	8.7 (2.2, 5.6–12.4)	*	*	$p = 0.027$
Duration (ms)	449 (94.8, 318–583)	457 (141.4, 284–877)	400 (113.1, 236–733)	$p = 0.035$	$p = 0.032$	n.s.
Left hemispace fixations						
Number	14.6 (5.8, 9.2–30.1)	13.5 (6.2, 6.8–28.0)	10.1 (2.3, 7.6–17.1)	*	*	n.s.
Duration (ms)	474 (104.3, 320–719)	436 (131.1, 255–750)	330 (83.3, 232–528)	*	*	n.s.
Rightward saccades						
Number	13.0 (5.3, 3.9–27.3)	16.9 (11.1, 4.4–45.9)	11.4 (2.3, 8.3–18.4)	n.s.	*	n.s.
Amplitude (°)	4.2 (0.8, 2.7–6.1)	4.7 (1.6, 2.1–9.2)	4.5 (0.8, 3.0–5.9)	n.s.	n.s.	$p = 0.062$
Leftward saccades						
Number	14.3 (7.5, 3.3–28.1)	14.9 (8.0, 6.2–37.0)	7.3 (3.3, 3.4–15.4)	*	*	n.s.
Amplitude (°)	4.8 (1.7, 2.7–9.2)	4.0 (0.8, 2.9–5.6)	4.8 (0.7, 3.3–6.1)	n.s.	*	$p = 0.027$

Statistical comparisons were made between LHH, RHH, and *N* (one-tailed dependent samples *t*-tests).
n.s. indicates non-significant comparisons.
* $p < 0.017$ (α_{corr}); *p*-values are given for marginally significant results.

Table 3
Saccadic accuracy in left- and right-sided simulated hemianopia (LHH, RHH) and in the normal viewing condition (*N*) [mean (S.D., range)].

	LHH	RHH	*N*	*N*–LHH	*N*–RHH	LHH–RHH
Initial rightward saccades						
Amplitude (°)	18.7 (1.0, 16.0–20.4)	18.6 (1.4, 14.3–20.6)	19.3 (0.7, 17.8–20.5)	*	$p = 0.034$	n.s.
Saccadic gain	0.97 (0.05, 0.83–1.05)	0.96 (0.07, 0.74–1.06)	1.00 (0.04, 0.92–1.06)	*	$p = 0.034$	n.s.
Normal saccades (%)	81.6 (20.1, 22.4–100.0)	64.8 (24.8, 4.8–95.2)	86.0 (15.5, 57.9–100.0)	n.s.	*	*
Hypometric saccades (%)	10.5 (17.3, 0–72.9)	18.6 (22.4, 0–95.2)	2.5 (7.9, 0–32.5)	*	*	n.s.
Hypermetric saccades (%)	7.9 (11.5, 0–41.7)	16.6 (20.4, 0–63.5)	11.5 (13.7, 0–40.0)	n.s.	n.s.	n.s.
Initial leftward saccades						
Amplitude (°)	18.0 (1.1, 15.6–19.6)	17.7 (1.0, 16.2–19.3)	18.5 (0.7, 16.9–19.4)	$p = 0.059$	*	n.s.
Saccadic gain	0.93 (0.06, 0.80–1.01)	0.91 (0.05, 0.83–0.99)	0.95 (0.04, 0.87–1.00)	$p = 0.059$	*	n.s.
Normal saccades (%)	72.5 (17.0, 33.3–90.7)	75.0 (14.9, 47.6–97.0)	86.1 (12.0, 61.1–100.0)	*	*	n.s.
Hypometric saccades (%)	20.0 (16.0, 0–57.4)	20.0 (12.8, 3.0–42.1)	7.3 (7.0, 0–23.1)	*	*	n.s.
Hypermetric saccades (%)	7.5 (9.2, 0–30.4)	4.9 (7.2, 0–23.3)	6.7 (10.9, 0–34.1)	n.s.	n.s.	n.s.

Statistical comparisons were made between LHH, RHH, and *N* (one-tailed dependent samples *t*-tests).
n.s. indicates non-significant comparisons.
[*] $p < 0.017$ (α_{corr}); *p*-values are given for marginally significant results.

condition and hemispace/direction for fixation number and saccadic amplitude (smaller $F_{(2,32)} = 4.49$, $p = 0.019$). During visual exploration with RHH, significantly more fixations were spent in right than in left hemispace, and rightward saccadic amplitudes were significantly larger than leftward amplitudes (smaller $t_{(16)} = -2.44$, $p = 0.014$, one-tailed). In LHH, leftward saccadic amplitudes were marginally larger than rightward ($t_{(16)} = 1.66$, $p = 0.059$, one-tailed). Visual exploration with RHH was associated with the highest number and duration of right-hemispace fixations and more and larger rightward saccades whereas visual exploration with LHH was associated with the highest number and duration of left-hemispace fixations. Eye-movement patterns during visual exploration with LHH and RHH were both distinguished by a higher number of leftward saccades than in the normal viewing condition (Table 2).

2.2.3. *The effect of simulated HH on saccadic accuracy*

Saccadic accuracy of healthy participants was also affected by simulated HH (Table 3), as indicated by a significant effect of simulation condition for the majority of saccadic accuracy measures (smallest $F_{(2,30)} = 3.41$, $p = 0.046$). The amplitude and gain of initial left- and rightward saccades was smaller when confronted with simulated LHH or RHH than in the normal viewing condition (yet, the LHH–*N* difference for leftward saccades and the RHH–*N* difference for rightward saccades were only marginally significant). Although we did not obtain a significant effect of simulation condition for the frequency of hypermetric left- and rightward saccades (larger $F_{(1.3,21.3)} = 2.37$, $p = 0.132$), the frequency of hypometric left- and rightward saccades was significantly higher, and that of normal saccades lower, when confronted with LHH and RHH. There were no significant differences between LHH and RHH (except for the frequency of normal rightward saccades that was lower with RHH).

2.2.4. *Subjective reports*

Participants' reports on the effects of simulated HH on reading were in close agreement with the objective test results (for a selection of representative quotes, see Table 4). All participants reported severe impairments of reading, visual exploration, and saccadic accuracy when confronted with simulated HH. They found reading with simulated HH more difficult than visual exploration (except for three participants). Reading with simulated RHH was more difficult than reading with simulated LHH, yet, participants experienced no such differential effects in the visual exploration and saccadic accuracy task. Reading with simulated HH was described as extremely slow, laborious and fatiguing, and participants reported that they missed syllables and words on the side of the simulated HH. RHH greatly impaired the ability to move the eyes smoothly along each line of text whereas LHH impaired the ability to find the beginning of the new line. During visual exploration, participants experienced difficulties in finding the way through the dots without losing their place; concentrating on moving the eyes and keeping count at the same time was described as very difficult. Participants considered the effect of simulated HH on saccadic accuracy to be minor.

Table 4
Subjective reports on the effects of simulated HH on reading, visual exploration and saccadic accuracy (selection of representative verbatim quotes).

Reading
"The text consisted of half-words and reading was hesitant."
"It was very difficult to make an eye-movement to the next word that was always covered by the visual defect."
"It was extremely difficult to concentrate on moving the eyes and understanding text at the same time."
"Reading with left-sided blindness was easier than with right-sided blindness because as soon as one knows where the lines begin sweeping the eyes back becomes less difficult."

Visual exploration
"One could never be certain whether one had missed dots or not whereas missing a word instantly resulted in comprehension difficulties."
"Eye-movements don't have to be as precise as in reading because you don't have to fixate each dot whereas in reading each word has to be fixated for understanding the text."

Saccadic accuracy
"Although one could not see the dot on the side of the simulated HH, its location was predictable after performing a few gaze shifts."

2.3. *Discussion*

2.3.1. *The effect of simulated HH on reading*

The main effect of simulated HH on reading performance was to induce a pronounced increase in reading time, which was paralleled by a severe alteration of the oculomotor reading pattern. Simulated HH led to a considerable increase in number and duration of fixations and repeated fixations. The decrease in forward and return-sweep saccadic amplitude and the consequent increase in number of forward saccades further contributed to the reduction in reading performance. Simulated HH seemed to provoke an inefficient oculomotor text processing strategy, which was also reflected by significantly prolonged and disorganised scanpaths. The side of the simulated visual field defect determined the severity of the resulting reading impairment. Reading a text passage with simulated RH required three times longer than under normal viewing conditions whereas it required only twice as much time with simulated LHH. The oculomotor reading patterns associated with simulated RHH were distinguished by a much higher number and duration of fixations, smaller and many more saccades and a much longer scanpath than those associated with simulated LHH; only the rate of repeated fixations was equally affected by simulated LHH and RHH. These observations replicate those obtained in hemianopic patients with hemianopic dyslexia (e.g. Leff et al., 2000; McDonald et al., 2006; Spitzyna et al., 2007; Trauzettel-Klosinski & Brendler, 1998; Zihl, 1995a, 2000) and are consistent with prior studies using gaze-contingent display paradigms to examine reading without parafoveal vision in healthy people (Cummings & Rubin, 1992; Fine & Rubin, 1999a; Ikeda & Saida, 1978; McConkie & Rayner, 1975, 1976; Rayner & Bertera, 1979; Rayner et al., 1981, 2006). Moreover, subjective reports are also in accordance with those of hemianopic patients (Kerkhoff, Münßinger, Eberle-Strauss, & Stögerer, 1992; Kerkhoff, Schaub, & Zihl, 1990; Zihl, 2000). Thus, our findings suggest that simulated HH induces the hemianopic reading impairment in healthy participants.

Yet, our observation that simulated LHH and RHH led to a similar decrease of the return-sweep amplitude departs from that obtained in hemianopic patients in which only left-sided visual field defects are associated with smaller return-sweep saccades (Mackensen, 1962; Zihl, 1995a). Inter-individual differences regarding the impact of simulated HH on the return-sweep, as indicated by a large variation in individual return-sweep amplitudes (range: 11.8–19.1), may account for this inconsistent finding. One may speculate that, at least in some participants, the return-sweep might have quickly improved after reading a few lines. The fixed horizontal position of the return-sweep's saccadic target, i.e. the first word of the next line, may have alleviated the adverse effects of simulated LHH on the visual guidance of the return-sweep. This has been reported for some patients with LHH after brain injury (Gassel & Williams, 1963), and is consistent with subjective reports of our participants.

2.3.2. *The effect of simulated HH on visual exploration*

Simulated HH also had a profound effect on visual exploration. It led to elevated visual exploration times and a higher number of errors, which were paralleled by alterations of the oculomotor visual exploration pattern. Exploring and counting the presented dots with simulated LHH or RHH required twice as much time as under normal viewing conditions, and participants made more errors in counting the dots. Simulated HH induced an inefficient and unsystematic oculomotor scanpath for exploring and processing the visual information in the visual exploration task, as indicated by the increase in number and duration of fixations as well as in scanpath length. Simulated HH also affected saccadic amplitudes, albeit to a much lesser degree. Unlike in reading, there were no performance differences between simulated LHH and RHH. The side of the simulated visual field defect only seemed to determine the horizontal fixation distribution, i.e. whether more and longer fixations are spent in left or right hemispace, as well as the properties of directional oculomotor measures, i.e. whether more left- or rightward saccades are being made. Our observations are consistent with those obtained in hemianopic patients showing the hemianopic visual exploration impairment (Gassel & Williams, 1963; Ishiai, Furukawa, & Tsukagoshi, 1987; Meienberg et al., 1981; Mort & Kennard, 2003; Pambakian, Mannan, Hodgson, & Kennard, 2004; Pambakian et al., 2000; Tant et al., 2002; Zihl, 1995b, 1999) as well as with studies dealing with visual exploration in simulated and real HH (Tant et al., 2002; Zangemeister & Oechsner, 1999; Zangemeister & Utz, 2002). Furthermore, subjective reports are also in accordance with those of hemianopic patients (Zihl, 1995b, 2000). Thus, our findings suggest that simulated HH also induces the hemianopic visual exploration impairment in healthy participants.

Yet, contrary to the common observation in hemianopic patients that saccades directed to the affected hemifield are smaller (hypometric) than those of saccades to the unaffected field (Ishiai et al., 1987; Meienberg et al., 1981; Tant et al., 2002; Zihl, 1995b, 1999), simulated HH resulted in participants making *larger* (hypermetric or overshooting) saccades in the direction of the affected hemifield. This discrepancy may be explained by inter-individual differences regarding the impact of simulated HH on visual exploration. Large variations in individual saccadic amplitudes to the right during visual exploration with simulated RHH (range: 2.1–9.2) and in those to the left during visual exploration with simulated LHH (range: 2.7–9.2) suggest that some participants quickly have adopted an efficient oculomotor strategy to compensate for simulated HH by making large saccades into the affected hemifield while others have not.

2.3.3. *The effect of simulated HH on saccadic accuracy*

Saccadic accuracy was also affected by simulated HH, albeit to a lesser extent than reading and visual exploration. Simulated HH induced saccadic dysmetria in healthy participants while they performed voluntary horizontal saccadic eye-movements to visual targets, leading to a reduction in saccadic accuracy. When confronted with simulated LHH or RHH, participants showed hypometric saccades in the direction of their affected hemifield, i.e. participant's saccades undershoot the position of visual targets located in their blind hemifield whereas, during normal viewing, participants made only few hypometric saccades. As in visual exploration, the side of simulated HH did not determine the severity of saccadic dysmetria. These observations are in accordance with reports on saccadic dysmetria in hemianopic patients (Meienberg et al., 1981; Schoepf & Zangemeister, 1993; Zangemeister, Oechsner, & Freska, 1995; Zangemeister & Utz, 2002; Zihl, 2000) and replicate those of a recent study that investigated saccadic accuracy in simulated HH (Zangemeister & Utz, 2002).

Yet, the saccadic accuracy impairment seemed to be less pronounced in simulated HH than in hemianopic patients. Group means indicate that hypometric saccades to the affected hemifield were less frequent and normal saccades more frequent in our participants than in patients (hypometria: ~20% vs. ~45%, normal saccades: ~67% vs. 30%, respectively) (Zihl, 2000). This inconsistent finding may be accounted for by inter-individual differences in the impact of simulated HH. The large variation in the frequency of hypometric saccades to the affected hemifield (range 0–95.2%), together with participants' reports, suggest that some participants quickly made use of the fixed target positions to accurately guide predictive saccades to the visual targets (Zangemeister & Utz, 2002).

3. Experiment 2: spontaneous oculomotor adaptation to simulated HH in reading (Experiment 2a) and visual exploration (Experiment 2b)

To determine whether and to what extent healthy participants spontaneously adapt to simulated HH in reading and visual exploration, we conducted two further experiments that investigated the effect of uninstructed reading (Experiment 2a) and visual exploration practice (Experiment 2b) on reading and visual exploration with simulated HH, respectively.

3.1. *Methods*

3.1.1. *Participants*

In Experiment 2a, we tested twelve participants (3 males, 9 females; mean age: 19.4 years (S.D.: 1.3); years of education: 12.6 years (S.D.: 0.8)) for investigating spontaneous oculomotor adaptation to simulated HH in reading. In Experiment 2b, we tested a new group of 13 participants (3 males, 10 females; mean age: 18.7 years (S.D.: 0.9); years of education: 12.2 years (S.D.: 0.6)) for investigating spontaneous oculomotor adaptation in visual exploration.

3.1.2. *Eye-movement recording, simulating HH, and the assessment of reading and visual exploration*

Methods for eye-movement recording, simulating HH and for assessing reading and visual exploration performance were identical to those used in Experiment 1.

3.1.3. *Procedure*

The procedures of Experiments 2a and 2b were identical. In Experiment 2a, participants performed two reading practice sessions: one session with simulated LHH, one with RHH (time spent practicing reading was ~15 min in each case). The sequence of simulation conditions, i.e. starting with LHH or RHH, was counterbalanced. We assessed reading performance and eye-movements (one text passage out of four) before and after the LHH-practice session and before and after the RHH-practice session. Between sessions, i.e. after the first post-practice assessment, a short break of 10 min was given. Task performance without any simulated HH (*N*) as well as each participant's subjective experience was obtained at the end of the experiment. In Experiment 2b, participants performed two visual exploration practice sessions: one session with simulated LHH, one with RHH (time spent practicing visual exploration was ~15 min in each case). Visual exploration performance and eye-movements (five trials) were assessed before and after the LHH- and RHH-practice session.

Materials for the reading practice sessions (Experiment 2a) consisted of 2 sets of 10 text passages taken from Michael Ende's (1974) "The grey gentlemen"; the text sets were counterbalanced between LHH- and RHH-practice sessions. None of the participants had read this novel before. Characteristics and presentation mode of the practice text passages were identical to those of the text passages used for the assessment of reading performance. During a practice session, participants were asked to read 10 consecutively presented texts. They were asked to read each text 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 provide evidence that participants had read each text, they were asked to reiterate its content immediately after reading the text, which all participants did correctly. The practice session gave participants the opportunity to learn how to read with a simulated HH without specific advice.

Materials for visual exploration practice sessions (Experiment 2b) consisted of 2 sets of 30 trials of the visual exploration task used for assessing visual exploration performance. During a practice session, patients were asked to silently count the dots of each of the 30 consecutively presented stimulus patterns as accurately and quickly as possible and to report the number of counted dots. No instruction was given on the number of dots or how to proceed with counting or searching; participants received no feedback on the number of counted dots. The practice session gave participants the opportunity to learn how to explore abstract patterns with a simulated HH without specific advice.

In order to disentangle the effects of adaptation to simulated HH from performance changes due to mere practice effects, a new group of six participants (6 females; mean age: 18.8 (S.D.: 0.8); all had 12 years of education) performed the same experimental protocol without any simulated HH in Experiment 2a (control condition); the control sample in Experiment 2b consisted of five participants (1 male, 4 females; mean age: 18.6 (S.D.: 0.5); all with 12 years of education).

3.1.4. *Data analyses*

For testing the effects of simulated HH on pre- and post-practice reading (Experiment 2a) and visual exploration performance (Experiment 2b), we conducted the same analyses as in Experiment 1. For testing the effects of practice, we performed a repeated measures ANOVA with simulation condition (LHH, RHH) and time (pre-, post-practice) as a within-subject factors in Experiments 2a and 2b. Post hoc paired comparisons between simulation conditions and time points were performed using repeated measures *t*-tests. Corrections for violations of sphericity assumptions and multiple comparisons were identical to those used in Experiment 1. We used Friedman nonparametric analyses of variance to test for overall effects of time (pre-, post-practice1, pre-, post-practice2, *N*-condition) in the control samples because of the small sample size. Post hoc paired comparisons were performed using Wilcoxon tests (two-tailed, $p < 0.05$, Bonferroni-correction). In Experiment 2b, 4.3% of trials were excluded.

3.2. *Results*

3.2.1. *Reading and visual exploration with simulated HH before practice*

The effects of simulated HH on reading before practice (Experiment 2a) were identical to those found in Experiment 1 (Tables 5 and 6), as indicated by a significant effect of simulation condition (LHH, RHH, *N*) for reading time and all oculomotor parameters (smallest $F_{(2,22)} = 8.57$, $p = 0.002$). In addition, we obtained significant differences between simulation conditions for the amplitude of return-sweep; reading with simulated LHH was characterised by the smallest return-sweeps.

The effects of simulated HH on visual exploration before practice (Experiment 2b) were also identical to those found in Experiment 1 (Tables 7 and 8), as indicated by a significant effect of simulation condition for visual exploration time, number of errors, and for all oculomotor parameters (smallest $F_{(2,24)} = 3.56$, $p = 0.044$); consistent with Experiment 1, there was no significant effect for overall, left- and rightward saccadic amplitude (largest $F_{(2,24)} = 2.17$, $p = 0.136$). We also replicated the results of the directional and

Table 5

Pre- and post-practice reading performance and related oculomotor measures in left- and right-sided simulated hemianopia (LHH, RHH) in comparison with the normal viewing condition (*N*) [mean (S.D., range)].

	LHH		RHH		*N*
	Pre	Post	Pre	Post	
Reading time (s)	32.4 (12.3, 12.7–56.5)	20.7 (5.5, 11.2–27.4)	63.8 (30.8, 43.2–156.3)	35.6 (13.4, 22.8–63.1)	16.9 (4.4, 9.9–26.1)
Total fixations					
Number	106.4 (40.5, 56.0–210.0)	80.9 (19.5, 54.0–111.0)	164.8 (71.7, 100.0–380.0)	127.8 (48.5, 84.0–241.0)	70.9 (21.6, 50.0–130.0)
Duration (ms)	254 (49.6, 186–347)	214 (37.0, 164–274)	320 (50.5, 263–431)	234 (36.9, 177–287)	192 (25.2, 149–245)
Repeated fixations (%)	22.3 (10.8, 5.4–48.1)	13.6 (6.4, 5.6–23.6)	22.9 (10.3, 4.4–39.2)	16.4 (8.8, 2.7–28.6)	11.8 (6.8, 3.5–23.1)
Forward saccades					
Number	63.5 (19.2, 34.0–98.0)	50.9 (13.2, 35.0–72.0)	110.9 (42.4, 53.0–211.0)	84.5 (32.8, 51.0–150.0)	48.5 (13.7, 29.0–85.0)
Amplitude (°)	4.0 (1.0, 2.5–5.5)	4.4 (0.9, 3.2–5.6)	2.8 (1.0, 1.7–4.8)	3.5 (1.0, 1.9–5.3)	4.4 (0.8, 3.3–5.8)
Return-sweep amplitude (°)	14.2 (1.8, 11.0–17.0)	16.6 (1.7, 13.8–20.2)	16.7 (1.6, 14.6–20.1)	17.5 (1.6, 15.4–20.5)	17.1 (1.8, 13.9–19.6)
Scanpath length (°)	483.7 (82.4, 369.2–680.2)	410.2 (48.9, 283.4–459.1)	586.8 (119.1, 460.1–918.6)	503.8 (88.6, 373.9–745.6)	403.6 (67.9, 307.2–540.5)

Table 6
Dependent samples *t*-tests (one-tailed) for analysing mean differences in reading performance and oculomotor measures between left- and right-sided simulated hemianopia (LHH, RHH) and the normal viewing condition (*N*) before and after practice (pre, post).

	N–LHH		*N*–RHH		LHH–RHH	
	Pre	Post	Pre	Post	Pre	Post
Reading time (s)	*	*	*	*	*	*
Total fixations						
Number	*	0.049	*	*	*	*
Duration (ms)	*	0.038	*	*	*	n.s.
Repeated fixations (%)	*	n.s.	*	0.045	n.s.	n.s.
Forward saccades						
Number	*	n.s.	*	*	*	*
Amplitude (°)	n.s.	n.s.	*	*	*	0.021
Return-sweep amplitude (°)	*	n.s.	n.s.	n.s.	*	n.s.
Scanpath length (°)	*	n.s.	*	*	*	*

n.s. indicates non-significant comparisons.

[*] $p < 0.017$ (α_{corr}); *p*-values are given for marginally significant results.

hemispace analyses; although only the interaction between simulation condition and direction for number of saccades reached statistical significance ($F_{(1.2,14.3)} = 11.38$, $p = 0.003$), post hoc comparisons revealed that visual exploration with simulated RHH was associated not only with significantly more right- than leftward saccades but also with more right- than left-hemispace fixations (vice versa for LHH-performance; smallest $t_{(12)} = -2.60$, $p = 0.012$; one-tailed).

3.2.2. *The effect of practice on reading and visual exploration with simulated HH*

Practicing reading with simulated LHH or RHH (Experiment 2a) led to an improvement in reading performance and related eye-movements (Table 5), as indicated by a significant effect of time for reading time and all oculomotor parameters (smallest $F_{(1,11)} = 7.79$, $p = 0.018$). Significant pre–post-differences for both LHH and RHH confirm this finding (smallest $t_{(11)} = -2.20$, $p = 0.025$; marginal significance for the amplitude of forward saccades in LHH ($t_{(11)} = -1.37$, $p = 0.061$)). We obtained a significant effect of simulation condition (LHH, RHH) for reading time and all oculomotor parameters (smallest $F_{(1,11)} = 4.90$, $p = 0.049$), except for fixation repetitions ($F_{(1,11)} = 0.37$, $p = 0.558$). The significant interaction between time and simulation condition for reading time and return-sweep amplitude (smaller $F_{(1,11)} = 7.11$, $p = 0.022$) can be explained by a significantly larger decrease in reading time for RHH (−28.2 s) than for LHH (−11.6 s) ($t_{(11)} = 2.81$, $p = 0.017$), and by a significantly larger increase in return-sweep amplitude for LHH (+2.4°) than for RHH (+0.8°) ($t_{(11)} = 2.67$, $p = 0.022$).

Table 8
Dependent samples *t*-tests (one-tailed) for analysing mean differences in visual exploration performance and oculomotor measures between left- and right-sided simulated hemianopia (LHH, RHH) and the normal viewing condition (*N*) before and after practice.

	N–LHH		*N*–RHH		LHH–RHH	
	Pre	Post	Pre	Post	Pre	Post
Visual exploration time (s)	*	*	*	*	n.s.	n.s.
Number of errors	*	n.s.	*	n.s.	n.s.	n.s.
Total fixations						
Number	*	*	*	*	n.s.	n.s.
Duration (ms)	*	n.s.	*	n.s.	n.s.	n.s.
Saccadic amplitude (°)	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Scanpath length (°)	*	n.s.	*	n.s.	n.s.	n.s.
Right hemispace fixations						
Number	*	n.s.	*	*	0.048	n.s.
Duration (ms)	*	n.s.	*	n.s.	n.s.	n.s.
Left hemispace fixations						
Number	*	*	*	0.018	n.s.	n.s.
Duration (ms)	*	0.030	*	n.s.	n.s.	n.s.
Rightward saccades						
Number	n.s.	n.s.	*	*	*	*
Amplitude (°)	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Leftward saccades						
Number	*	*	*	0.026	*	*
Amplitude (°)	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

n.s. indicates non-significant comparisons.

[*] $p < 0.017$ (α_{corr}); *p*-values are given for marginally significant results.

After reading practice, we still obtained a significant effect of simulation condition (LHH, RHH, *N*) for reading time and all

Table 7
Pre- and post-practice visual exploration performance and related oculomotor measures in left- and right-sided simulated hemianopia (LHH, RHH) in comparison with the normal viewing condition (*N*) [mean (S.D., range)].

	LHH		RHH		*N*
	Pre	Post	Pre	Post	
Visual exploration time (s)	12.0 (2.9, 6.9–13.8)	9.6 (2.1, 6.1–11.8)	13.6 (2.7, 8.8–18.5)	9.4 (1.5, 6.9–11.9)	6.8 (1.1, 4.9–8.2)
Number of errors	0.6 (0.6, 0–1.8)	0.1 (0.1, 0–0.4)	0.8 (0.8, 0–2.4)	0.1 (0.1, 0–0.3)	0.2 (0.1, 0–0.4)
Total fixations					
Number	24.0 (6.5, 14.6–36.3)	19.8 (5.3, 9.2–28.4)	26.8 (8.0, 15.0–47.6)	21.1 (4.3, 14.8–28.0)	16.1 (3.0, 10.6–20.8)
Duration (ms)	463 (100.6, 349–699)	407 (113.6, 265–666)	449 (116.2, 317–749)	381 (117.8, 252–719)	361 (60.1, 299–481)
Saccadic amplitude (°)	3.9 (0.8, 2.4–5.2)	3.5 (0.8, 2.0–5.3)	3.7 (0.9, 2.1–4.8)	3.5 (0.9, 2.2–5.5)	4.0 (0.5, 2.6–4.6)
Scanpath length (°)	89.4 (29.2, 51.4–155.8)	73.2 (29.6, 30.7–132.0)	95.5 (32.0, 45.2–168.9)	74.0 (21.0, 42.4–117.3)	64.0 (14.5, 37.2–91.8)
Right hemispace fixations					
Number	11.1 (3.4, 7.8–17.0)	10.0 (4.4, 5.0–23.0)	13.6 (3.6, 7.0–19.7)	13.0 (4.6, 6.4–24.0)	8.6 (1.9, 5.0–11.6)
Duration (ms)	468 (86.0, 360–583)	411 (94.6, 244–580)	461 (135.3, 307–793)	382 (109.1, 232–658)	385 (91.8, 311–643)
Left hemispace fixations					
Number	11.4 (3.4, 6.8–16.2)	11.2 (3.9, 4.2–17.6)	10.9 (2.8, 4.4–14.7)	10.3 (4.4, 6.0–23.6)	7.6 (2.2, 5.0–12.2)
Duration (ms)	446 (145.6, 289–778)	433 (154.4, 284–852)	444 (103.0, 331–708)	387 (142.4, 260–796)	350 (58.8, 273–430)
Rightward saccades					
Number	8.7 (3.7, 4.0–17.0)	7.6 (5.8, 3.0–25.3)	16.8 (6.2, 4.0–24.3)	15.5 (6.9, 3.6–26.4)	10.9 (3.1, 5.4–16.0)
Amplitude (°)	3.9 (1.1, 2.4–7.0)	3.7 (1.0, 2.4–6.1)	3.7 (1.0, 2.0–5.3)	3.9 (1.4, 2.1–6.2)	4.0 (0.6, 2.5–4.7)
Leftward saccades					
Number	14.3 (5.4, 4.2–22.2)	14.0 (5.5, 4.4–20.0)	7.8 (2.8, 3.0–14.0)	7.9 (5.0, 4.0–21.2)	5.2 (2.4, 1.6–10.6)
Amplitude (°)	4.0 (1.1, 2.4–5.3)	4.2 (2.3, 1.9–10.6)	3.7 (0.7, 2.1–4.8)	3.5 (0.8, 2.4–5.3)	4.2 (0.9, 2.7–6.1)

oculomotor parameters (smallest $F_{(2,22)} = 5.73$, $p = 0.010$), except for fixation repetitions and the return-sweep amplitude (larger $F_{(2,22)} = 1.73$, $p = 0.20$). Yet, mean differences in reading time between the simulated HH and normal viewing condition were much smaller (LHH: 3.8 s, RHH: 18.7 s) than before practice (LHH: 15.5 s, RHH: 45.5 s). Analysing the differential effects of LHH and RHH on practice outcome revealed that practicing reading with RHH led to less improvement than practicing reading with LHH; the reading performance participants regained was closer to normal during with LHH than with RHH. Yet, although practicing reading with LHH or RHH significantly reduced the reading impairment caused by the hemianopic visual field defect, reading performance and eye-movements still differed from normal reading after practice (Table 6).

Practicing visual exploration with simulated LHH or RHH (Experiment 2b) led to a significant improvement in visual exploration performance and related eye-movements (Table 7), as indicated by a significant effect of time for visual exploration time, number of errors, and for number and duration of fixations and scanpath length (smallest $F_{(1,12)} = 5.13$, $p = 0.043$). Significant pre-post-differences for LHH and RHH confirm this finding (smallest $t_{(11)} = -2.20$, $p = 0.025$). Consistent with pre-practice analyses, there was no significant effect for overall, left- and rightward saccadic amplitude; practice did also not affect number and duration of left- and right-hemispace fixations (largest $F_{(1,12)} = 2.49$, $p = 0.141$). In contrast to reading practice, visual exploration performance and eye-movements measures as well as the overall practice outcome were not differentially affected by the side of simulated HH (non-significant effect of simulation condition and of its interaction with time, largest $F_{(1,12)} = 3.60$, $p = 0.082$); only the number of left- and rightward saccades differed significantly between LHH and RHH, both before and after practice (significant effect of simulation condition, smaller $F_{(1,12)} = 8.89$, $p = 0.011$).

The absence of a significant effect of simulation condition (LHH, RHH, *N*) for number of errors, duration of overall, left- and right-hemispace fixations, scanpath length, and duration of left- and right-hemispace fixations after practice indicates that participants regained normal performance with regard to these visual exploration measures despite LHH or RHH (largest $F_{(2,24)} = 2.54$, $p = 0.100$; see also Tables 7 and 8). Yet, visual exploration time and the number of overall, left- and right-hemispace fixations and of left- and rightward saccades were still elevated, albeit to a lesser extent (smallest $F_{(1.2,14.6)} = 5.03$, $p = 0.035$). Although the differences for visual exploration time still reached statistical significance, they were very small (LHH–*N*: 2.9 s, RHH–*N*: 2.6 s) and are unlikely to reflect any meaningful performance difference, especially when considering that visual exploration with LHH and RHH were as accurate as normal performance after practice. However, visual exploration with RHH was still characterised by significantly more right-hemispace fixations and rightward saccades that were also more frequent than left-hemispace fixations and leftward saccades; we obtained the converse pattern for visual exploration with LHH (see Table 8; significant interaction between simulation condition and hemispace/direction, smaller $F_{(2,24)} = 3.77$, $p = 0.038$; smallest $t_{(12)} = 2.51$, $p = 0.014$; one-tailed).

3.2.3. Subjective reports

Participants' subjective reports were in close agreement with the effects of simulated HH on reading (Experiment 2a) and visual exploration (Experiment 2b) as well as with the effects of reading and visual exploration practice as verified by objective test results (for a selection of representative quotes, see Table 9). Subjective reports on pre-practice reading and visual exploration performance were similar to those obtained in Experiment 1. After reading practice (Experiment 2a), all participants reported an improvement in reading, which was described as an increase in the ability to efficiently identify words and guide eye-movements through the text despite simulated HH. Participants reported to have developed specific reading strategies which reduced omission and guessing errors, diminished the need to re-read words, and improved text comprehension; to guide their eye-movements during reading with simulated LHH, they reported to have made use of the fixed left text boundary. Reading with simulated LHH was experienced as more or less normal after practice whereas reading with simulated RHH was still considered as impaired, albeit to a lesser extent. After visual exploration practice (Experiment 2b), all participants reported an improvement in visual exploration performance, which was described as an increase in the ability to quickly gain a complete overview of each stimulus pattern and accurately count all dots despite simulated HH; participants also stated that they were much more confident about which dots have already been seen and counted than before practice. Participants reported to have quickly adopted a more efficient eye-movement strategy for dot counting. After practice, visual exploration with simulated HH was described as being normal.

Table 9
Subjective reports on the effects of practicing reading and visual exploration with simulated HH (selection of representative verbatim quotes).

Reading practice
"I got used to reading with half-blindness and reading became much easier."
"Over time, the technique for unveiling words and sentences got better."
"I tried to look past each word and see it as a whole before reading it."
"I tried to carry on in the flow of reading by imagining that there are more words to come that need to be looked at."
"I forced myself to follow each sentence although the rest of the sentence was not there."
Visual exploration practice
"After practice, exploring and counting dots with left or right half-blindness was normal."
"After practice, dot counting was much easier and quicker than in the beginning"
"Concentrating on eye-movements to unveil the dots and keeping count at the same time became less effortful."
"I tried to get a quick overview of the entire dot pattern by making large eye-movements and grouping dots."
"I overcompensated with the eyes into the blind field."

3.2.4. Practice effects in the control condition

In our control samples, we did not obtain a significant effect of time (Experiment 2a: largest $\chi^2_{(4)} = 7.07$, $p = 0.132$; Experiment 2b: largest $\chi^2_{(4)} = 9.36$, $p = 0.053$). Although there was a significant effect for forward and return-sweep saccadic amplitude and scanpath length in Experiment 2a (smaller $\chi^2_{(4)} = 10.40$, $p = 0.024$), no difference between any two of the four time points was significant (largest $Z = 2.20$, $p = 0.031$ (corrected level of significance: $p = 0.01$)); even if significant, these differences would be either too small to reflect any meaningful difference (0.5° and 0.6° for the amplitudes of forward and return-sweep saccades respectively) or even indicate maladaptation since scanpath length increased by 41.3°. In Experiment 2b, there was a significant effect for number of fixations and forward saccades, fixation duration and scanpath length (smallest $\chi^2_{(4)} = 9.76$, $p = 0.045$); yet, again, no difference between any two of the four time points reached statistical significance (largest $Z = -2.02$, $p = 0.063$).

3.3. Discussion

The main result of Experiment 2 is that reading (Experiment 2a) and visual exploration practice (Experiment 2b) without specific instruction led to significant improvements in reading and visual exploration with simulated HH, respectively. In addition, we replicated the effect of simulated HH on reading and visual exploration performance and associated eye-movement patterns found in Experiment 1, which is also congruent with previous reports on the hemianopic reading and visual exploration impairments in patients with HH. In addition, we complemented our findings from Experiment 1 by obtaining the differential effect of simulated LHH and RHH on the return-sweep in reading (Experiment 2a) as well as on the horizontal fixation distribution and directional oculomotor measures in visual exploration (Experiment 2b), which are typical for the hemianopic reading and visual exploration impairments (Zihl, 1995a, 1995b, 1999, 2000).

Reading practice effects were characterised by a considerable decrease in reading time, the effects of visual exploration practice by a decrease in exploration times and number of errors despite simulated LHH or RHH. Both improvements were accompanied by changes in the respective eye-movement patterns. In reading (Experiment 2a) participants made significantly fewer fixations and fixation repetitions and showed much shorter fixation durations. The amplitude of forward saccades and that of the return-sweeps increased, which led to a much smaller number of forward saccades. Participants seemed to extract the same amount of text information by using a much more efficient oculomotor text processing strategy, which is also reflected by the significant decrease in scanpath length. In visual exploration (Experiment 2b), they also showed significantly fewer fixations and shorter fixation durations. Although the differential distribution of fixations as well as the differential effect on directional oculomotor measures pertained after practice, participants seemed to have adopted a much more efficient oculomotor strategy for exploring and processing visual information, which is also reflected by significantly shorter and more systematic scanpaths. Although inter-individual differences of these changes were substantial (as indicated by a large variation in individual means before and after practice, see Table 4 (Experiment 2a) and 6 (Experiment 2b)) reading and visual exploration performance as well as oculomotor parameters improved significantly in all participants.

It is important to note that the improvements in reading and visual exploration and associated eye-movements cannot be attributed to increases in visual field sparing during the experimental sessions since the accuracy of the simulated visual field border was continuously monitored. The absence of performance changes during reading and visual exploration practice under normal viewing conditions shows that mere practice effects cannot account for the performance changes during reading practice with simulated HH. In addition, there was no evidence of a trade-off between speed and accuracy after practice, neither for reading nor for visual exploration performance. Before and after reading practice, participants reiterated the content of each text equally correctly, and visual exploration practice led to a significant decrease in number of errors.

Practice-related changes of oculomotor measures in reading (Experiment 2a) and visual exploration (Experiment 2b) seem to reflect spontaneous oculomotor adaptation to simulated HH, which is possibly best understood as functional reorganisation of the attentional top-down eye-movement control in reading (Schuett et al., 2008a) and visual exploration (Mort & Kennard, 2003). We assume that spontaneous oculomotor adaptation to simulated HH in reading and visual exploration emerges as a result of perceptual and oculomotor (procedural) learning processes in reading (Ofen-Noy, Dudai, & Karni, 2003) and visual exploration (Rogers, Lee, & Fisk, 1995), which are modulated by attention. These processes seem to occur spontaneously and rapidly when healthy participants are first confronted with a simulated HH, even in the absence of any instruction aimed at improving performance. Reading as few as only 10 short text passages and practicing visual exploration for as few as only thirty trials seems to suffice to facilitate spontaneous oculomotor adaptation processes, which alleviate the reading and visual exploration impairments resulting from this simulated visual-sensory deficit. Since eye-movements were not recorded binocularly, it remains possible that the improvements during reading practice were based on changes in fixation disparity. Although our participants may have compensated for simulated HH by increasing the magnitude and/or frequency of fixation disparity, the effects of such a strategy cannot fully account for the improvements we obtained. During normal reading, average fixation disparity ranges between 1–2 characters (40–50% of fixations) (Liversedge, Rayner, White, Findlay, & McSorley, 2006; Liversedge, White, Findlay, & Rayner, 2006). Since the visual system may tolerate fixation disparity only up to a certain point and reduced convergence leading to increased fixation disparity seems to be associated with a reduction in reading performance (Kirkby, Webster, Blythe, & Liversedge, 2008), the adaptation of fixation disparity during reading with simulated HH is limited. The resulting improvement of ~2 characters *per* fixation is, however, too small to explain the improvement in reading performance we obtained in our participants.

Hemianopic patients with impairments of reading and visual exploration in contrast require specific and systematic treatment to reinforce these oculomotor adaptation processes (Gassel & Williams, 1963; Zihl, 2000, 2003). About 10–15 oculomotor reading training sessions (a 45 min) and an equal amount of oculomotor scanning training is necessary for participants to regain sufficient reading and visual exploration performance (Zihl, 2000). The changes related to spontaneous oculomotor adaptation we found in our healthy participants are consistent with the treatment-related changes of hemianopic patients in reading (Schuett et al., 2008b; Zihl, 1995a, 2000) and visual exploration (Zihl, 1995b, 2000). Our findings are also in accordance with previous studies investigating spontaneous oculomotor adaptation to simulated central visual field loss in reading (Bernard, Scherlen, & Castet, 2007; Fornos, Sommerhalder, Rappaz, Pelizzone, & Safran, 2006; Sommerhalder et al., 2003, 2004) and with reports on spontaneous oculomotor adaptation to simulated hemianopic visual field loss in visual exploration (Zangemeister & Oechsner, 1999; Zangemeister & Utz, 2002).

Yet, there seems to be a differential effect of simulated LHH and RHH on the outcome of practice that is specific to reading. Reading 10 text passages with LHH led to greater improvements than reading the same amount of text with RHH; after practice, reading with LHH was closer to normal than reading with RHH, albeit that in either case reading still differed from that under normal viewing conditions. In contrast to reading, there was no such differential effect on the outcome of visual exploration practice. Practicing visual exploration for 30 trials led to the same improvements in visual exploration with simulated LHH and RHH. This finding is consistent with the differential effect of left- and right-sided visual field loss on the rehabilitation outcome of hemianopic patients receiving specific treatment for their reading and visual exploration impairments. Patients with RHH require twice as much reading training sessions to reach the same outcome as patients with LHH whereas an equal amount of training leads to the same improvements in visual exploration (Zihl, 1995a, 2000).

4. General discussion

The purpose of the reported experiments was to identify the visual components that may constitute the hemianopic reading and visual exploration impairments as well as to determine whether these impairments are purely visually elicited. We therefore examined the effects of simulated HH on reading, visual exploration and saccadic accuracy in healthy participants (Experiment 1). Furthermore, we investigated whether and to what extent healthy participants may spontaneously adapt to simulated HH in reading (Experiment 2a) and in visual exploration (Experiment 2b). Our findings suggest that the hemianopic visual field defect clearly contributes to the chronic impairments of reading and visual and exploration found in hemianopic patients although it may not be their sole cause.

In Experiment 1, we demonstrated that simulated HH produces the main features of the hemianopic reading and visual exploration impairments (as well as of its indicator saccadic accuracy) in healthy participants. These results show that the bottom-up restriction of the visual field clearly affects reading and visual exploration performance. Reading critically depends on the parafoveal visual field, which provides the basis for word identification and eye-movement control (Rayner, 1998), whereas efficient visual exploration requires global visual information extraction from the parafoveal and peripheral visual field for the attentional top-down control of eye-movements in space and local processing of fine details (Hochstein & Ahissar, 2002; Juan & Walsh, 2003). If vision in these visual field regions is affected, either by simulated HH or by brain injury, efficient word identification and the visual control of eye-movements in reading are impaired (Schuett et al., 2008a); since visual scenes are only partly visible, quickly gaining a complete overview becomes increasingly difficult and consequent impairments of global processing affect guiding the eyes through a scene for further local processing (Zihl, 2000).

The differential effect of simulated (or real) LHH and RHH on reading performance provides additional evidence for the visual basis of the hemianopic reading impairment. In left-to-right reading, right parafoveal vision is of greater importance than left parafoveal vision (McConkie & Rayner, 1976). Visual information to the right of fixation is critical to eye-movement control and enables efficient processing of the foveal and preprocessing of the parafoveal word whereas visual information to the left of fixation is mainly required for planning and guiding the return-sweep (Rayner, 1998). This explains why the hemianopic reading impairment is more pronounced in simulated (or real) RHH than in LHH. Our results are substantiated by a prior study showing that masking the right visual field imposes a greater limit to reading performance than masking the left visual field (Fine & Rubin, 1999a; see also Cummings & Rubin, 1992; Ikeda & Saida, 1978; McConkie & Rayner, 1975, 1976; Rayner et al., 1981, 2006). However, since the foveal visual field and parts of the contralateral parafoveal visual field were additionally obliterated in this study, the resulting reading impairment was more pronounced than in our participants (Fine & Rubin, 1999a). Occluding foveal vision, which is essential for word identification, makes reading almost impossible (Fine & Rubin, 1999b, 1999c; Rayner & Bertera, 1979; Rayner et al., 1981). That the greatest impairments of reading associated with a visual field disorder are found in patients with a central scotoma is consistent with this finding (Teuber, Battersby, & Bender, 1960; Zihl, 2000).

Yet, this differential effect seems to be specific to reading. Although the side of the hemianopic visual field defect determines the horizontal fixation distribution and properties of directional oculomotor measures in visual exploration, there are no performance differences between LHH and RHH. It does not determine the severity of the resulting impairment as it does in reading. Thus, there seems to be a stronger relationship between the visual-sensory defect and the resulting impairments in reading than in visual exploration. Further evidence stems from the observation that the extent of a visual field defect (as determined by visual field sparing) determines the severity of the resulting reading impairment but not that of the visual exploration (and saccadic accuracy) impairment (Zihl, 1995a, 1995b, 2000). Poppelreuter (1917/1990) therefore concluded that “the visual field defect as such does not itself significantly impair the process of visual search” (p. 113) and dismissed it as primary cause of the hemianopic visual exploration impairment; he also suggested that the reading impairment “caused by the hemianopia itself is not that substantial” (p. 223).

In Experiments 2a and 2b, we demonstrated that the hemianopic visual field defect is a necessary but possibly not a sufficient condition that causes the severe and long-lasting reading and visual exploration impairments in hemianopic patients. When our healthy participants were confronted with simulated HH, they initially presented the main features of the hemianopic reading and visual exploration impairments. Yet, relatively quickly, participants spontaneously adapted to simulated HH by developing efficient oculomotor compensation strategies that alleviated the reading and visual exploration impairments caused by this pure visual-sensory deficit. Participants regained close to normal visual exploration performance but reading with simulated HH, particularly with simulated RHH, remained impaired. Since the reading performance level was still higher than that of hemianopic patients, our results indicate that the visually elicited hemianopic reading and visual exploration impairments are not as severe and long-lasting as those found in hemianopic patients whose reading and visual exploration performance remains severely impaired even years after the occurrence of visual field loss (Gassel & Williams, 1963).

Our findings are consistent with observations that some hemianopic patients show efficient spontaneous oculomotor adaptation and regain normal performance very soon after brain injury (Gassel & Williams, 1963; Zihl, 2000, 2003). They are more likely to adapt to their visual field defect in visual exploration (~40% of cases) than in reading (~20%), and there seems to be a clear double dissociation between spontaneous oculomotor adaptation to visual field loss in visual exploration and reading (Zihl, 2000). These findings suggest task-specificity of spontaneous oculomotor adaptation to visual field loss, which may be explained by a task-specific functional specialisation of the (cortical) oculomotor system (Alahyane et al., 2007). This assumption is consistent with the view that control of visual processing and eye-movements in reading may be mediated by different neural networks than in visual exploration, albeit both networks probably overlap (Zihl, 1995a, 1995b, 2000).

In contrast to our participants, however, successful spontaneous oculomotor adaptation to visual field loss occurs only very rarely in patients. It seems to depend on whether postchiasmatic visual pathway injury is accompanied by injury to the fibre pathways and/or structures involved in the visual bottom-up and attentional top-down control of visual information processing and saccadic eye-movement in reading (Schuett et al., 2008a) and visual exploration (Zihl, 1995b, 2000). Patients whose brain injury is confined to the postchiasmatic visual pathway spontaneously adapt to their visual field loss and show normal reading and visual exploration performance (Zihl, 1995a, 1995b). Thus, vision is what the eyes (can) make of it. If the occipital white matter comprising subcortical–cortical reciprocal connections and/or to the posterior thalamus is additionally affected by brain injury, patients show severe and chronic impairments of reading (Zihl, 1995a). Impairments of visual exploration emerge and persist if patients show additional injury to the ipsilateral occipito-parietal cortex and/or posterior thalamus (Zihl, 1995b).

Observations of patients with normal visual fields and posterior parietal damage, showing the hemianopic visual exploration (and saccadic accuracy) impairment (Poppelreuter, 1917/1990; Zihl & Hebel, 1997), suggest that it is not the visual field defect but additional extrastriate brain injury that causes this impairment; a comparison between these patients and hemianopic patients with a similar posterior parietal involvement might clarify whether an accompanying visual field defect may exacerbate the visual exploration impairment. The hemianopic reading impairment, in contrast, seems to critically depend on the presence of a visual field defect. Although patients with normal visual fields and posterior parietal damage also reported difficulties in finding their way through lines of text on a page (Zihl & Hebel, 1997), no case of hemianopic dyslexia in patients with normal visual fields and occipital white matter and/or posterior thalamus injury has been reported thus far.

The high frequency of extra-striate lesions in patients with homonymous visual field loss (Hebel & von Cramon, 1987) explains why impairments of reading and visual exploration are commonly associated with hemianopic visual field defects. That these patients require systematic oculomotor training for at least 8 h (Zihl, 2000), whereas our participants showed improved reading or visual exploration performance after 15 min of uninstructed practice, provides further evidence that the visual field defect is an important but not the sole cause of the hemianopic reading and visual exploration impairments. That patients with extensive occipital white matter and/or occipito-parietal regions require the largest amount of training (Zihl, 1995a, 1995b, 2000) is consistent with this assumption. The greater importance of the visual field defect for the hemianopic reading impairment than for the visual exploration impairment is substantiated by the differential effect of left- and right-sided visual field loss on the treatment outcome in reading but not in visual exploration (Zihl, 1995a, 2000). Yet, our findings may be limited by the fact that we obtained our evidence on the basis of relatively young and well-educated healthy participants since the majority of hemianopic patients are over the age of 55 (Zihl, 2000) and age-related processes appear to play a significant role in spontaneous oculomotor adaptation to visual field loss (Tant et al., 2002).

In conclusion, these observations and our findings suggest that the visual field defect is a major component of the hemianopic reading impairment. It is likely, however, that additional injury to the occipital white matter and/or posterior thalamus is required for this impairment to persist. Although the visual field defect contributes to the hemianopic visual exploration impairment, it does not seem to be causative. In contrast to the hemianopic reading impairment, injury to the ipsilateral occipito-parietal cortex and/or posterior thalamus seems to be the primary cause. Hemianopic dyslexia and the impairment of visual exploration may be interpreted as disorders of the visual bottom-up and attentional top-down control of visual processing and eye-movements which masquerade as failures of vision.

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References

Alahyane, N., Salemme, R., Urquizar, C., Cotti, J., Guillaume, A., Vercher, J.-L., et al. (2007). Oculomotor plasticity: Are mechanisms of adaptation for reactive and voluntary saccades separate? *Brain Research*, *1135*, 107–121.

Bernard, J.-B., Scherlen, A.-C., & Castet, E. (2007). Page mode reading with simulated scotomas: A modest effect of interline spacing on reading speed. *Vision Research*, *47*, 3447–3459.

Cummings, R. W., & Rubin, G. S. (1992). Reading speed and saccadic eye movements with an artificial paracentral scotoma. *Investigative Ophthalmology and Visual Science*, *33*, 1418.

Ende, M. (1974). *The grey gentlemen*. London: Burke Books.

Fine, E. M., & Rubin, G. S. (1999a). Reading with simulated scotomas: Attending to the right is better than attending to the left. *Vision Research*, *39*, 1039–1048.

Fine, E. M., & Rubin, G. S. (1999b). The effects of simulated cataract on reading with normal vision and simulated central scotoma. *Vision Research*, *39*, 4274–4285.

Fine, E. M., & Rubin, G. S. (1999c). Reading with central field loss: Number of letters masked is more important than the size of the mask in degrees. *Vision Research*, *39*, 747–756.

Fornos, A. P., Sommerhalder, J., Rappaz, B., Pelizzone, M., & Safran, A. B. (2006). Processes involved in oculomotor adaptation to eccentric reading. *Investigative Ophthalmology and Visual Science*, *47*, 1439–1447.

Gassel, M. M., & Williams, D. (1963). Visual function in patients with homonymous hemianopia. Part II. Oculomotor mechanisms. *Brain*, *86*, 1–36.

Gray, L. G., Galetta, S. L., Siegal, T., & Schatz, N. J. (1997). The central visual field in homonymous hemianopia: Evidence for unilateral foveal representation. *Archives of Neurology*, *54*, 312–317.

Hebel, N., & von Cramon, D. (1987). Der Posteriorinfarkt [Posterior infarction]. *Fortschritte der Neurologie in der Psychiatrie*, *55*, 37–53.

Hochstein, S., & Ahissar, M. (2002). View from the top: Hierarchies and reverse hierarchies in the visual system. *Neuron*, *36*, 791–804.

Ikeda, M., & Saida, S. (1978). Span of recognition in reading. *Vision Research*, *18*, 83–88.

Ishiai, S., Furukawa, T., & Tsukagoshi, H. (1987). Eye-fixation patterns in homonymous hemianopia and unilateral spatial neglect. *Neuropsychologia*, *25*, 675–679.

Juan, C.-H., & Walsh, V. (2003). Feedback to V1: A reverse hierarchy in vision. *Experimental Brain Research*, *150*, 259–263.

Kerkhoff, G., Münßinger, G., Eberle-Strauss, G., & Stögerer, E. (1992). Rehabilitation of hemianopic alexia in patients with postgeniculate visual field disorders. *Neuropsychological Rehabilitation*, *2*, 21–42.

Kerkhoff, G., Schaub, J., & Zihl, J. (1990). Die Anamnese zerebral bedingter Sehstörungen [Anamnesis of cerebral visual disorders]. *Nervenarzt*, *61*, 711–718.

Kirkby, J. A., Webster, L. A. D., Blythe, H. I., & Liversedge, S. P. (2008). Binocular coordination during reading and non-reading tasks. *Psychological Bulletin*, *134*, 742–763.

Leff, A. P., Scott, S. K., Crewes, H., Hodgson, T. L., Cowey, A., Howard, D., et al. (2000). Impaired reading in patients with right hemianopia. *Annals of Neurology*, *47*, 171–178.

Lezak, M., Howieson, D. B., & Loring, D. W. (2004). *Neuropsychological assessment* (4th ed.). Oxford: Oxford University Press.

Liversedge, S. P., Rayner, K., White, S. J., Findlay, J. M., & McSorley, E. (2006). Binocular coordination of the eyes during reading. *Current Biology*, *16*, 1726–1729.

Liversedge, S. P., White, S. J., Findlay, J. M., & Rayner, K. (2006). Binocular coordination of eye movements during reading. *Vision Research*, *46*, 2363–2374.

Mackensen, G. (1962). Die Untersuchung der Lesefähigkeit als klinische Funktionsprüfung [Examining the ability to read as clinical functional analysis]. *Fortschritte in der Augenheilkunde*, *12*, 344–379.

Mauthner, L. (1881). *Gehirn und Auge [Brain and eye]*. Wiesbaden, Germany: Bergmann.

McConkie, G. W., & Rayner, K. (1975). The span of the effective stimulus during a fixation in reading. *Perception and Psychophysics*, *17*, 578–586.

McConkie, G. W., & Rayner, K. (1976). Asymmetry of the perceptual span in reading. *Bulletin of the Psychonomic Society*, *8*, 365–368.

McDonald, S. A., Spitzyna, G., Shillcock, R., Wise, R. J. S., & Leff, A. P. (2006). Patients with hemianopic alexia adopt an inefficient eye movement strategy when reading text. *Brain*, *129*, 158–167.

Meienberg, O., Zangemeister, W. H., Rosenberg, M., Hoyt, W. F., & Stark, L. (1981). Saccadic eye movement strategies in patients with homonymous hemianopia. *Annals of Neurology*, *9*, 537–544.

Mort, D. J., & Kennard, C. (2003). Visual search and its disorders. *Current Opinion in Neurology*, *16*, 51–57.

Ofen-Noy, N., Dudai, Y., & Karni, A. (2003). Skill learning in mirror reading: How repetition determines acquisition. *Brain Research, Cognitive Brain Research*, *17*, 507–521.

Pambakian, A. L. M., Mannan, S. K., Hodgson, T. L., & Kennard, C. (2004). Saccadic visual search training: A treatment for patients with homonymous hemianopia. *Journal of Neurology, Neurosurgery and Psychiatry*, *75*, 1443–1448.

Pambakian, A. L. M., Wooding, D. S., Patel, N., Morland, A. B., Kennard, C., & Mannan, S. K. (2000). Scanning the visual world: A study of patients with homonymous hemianopia. *Journal of Neurology, Neurosurgery and Psychiatry*, *69*, 751–759.

Pfeifer, R. A. (1919). Die Störungen des optischen Suchaktes bei Hirnverletzten [Disorders of the optic search act in the brain injured]. *Deutsche Zeitschrift fur Nervenheilkunde*, *64*, 140–152.

Poppelreuter, W. (1917/1990). *Disturbances of lower and higher visual capacities caused by occipital damage* (J. Zihl, & L. Weiskrantz, Trans.). Oxford, UK: Clarendon Press.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, *124*, 372–422.

Rayner, K., & Bertera, J. H. (1979). Reading without a fovea. *Science*, *206*, 468–469.

Rayner, K., Inhoff, A. W., Morrison, R. E., Sowiaczek, M. L., & Bertera, J. H. (1981). Masking foveal and parafoveal vision during eye fixations in reading. *Journal of Experimental Psychology: Human Perception and Performance*, *7*, 167–179.

Rayner, K., Liversedge, S. P., & White, S. J. (2006). Eye movements when reading disappearing text: The importance of the word to the right of fixation. *Vision Research*, *46*, 310–323.

Reinhard, J., & Trauzettel-Klosinski, S. (2003). Nasotemporal overlap in humans: A functional retinal ganglion cells study. *Investigative Ophthalmology and Visual Science*, *44*, 1568–1572.

Rogers, W. A., Lee, M. D., & Fisk, A. D. (1995). Contextual effects on general learning, feature learning, and attention strengthening in visual search. *Human Factors*, *37*, 158–172.

Schoepf, D., & Zangemeister, W. H. (1993). Correlation of ocular motor reading strategies to the status of adaptation in patients with hemianopic visual field defects. *Annals of the New York Academy of Sciences*, *682*, 404–408.

Schuett, S., Heywood, C. A., Kentridge, R. W., & Zihl, J. (2008a). The significance of visual information processing in reading: Insights from hemianopic dyslexia. *Neuropsychologia*, *46*, 2441–2458.

Schuett, S., Heywood, C. A., Kentridge, R. W., & Zihl, J. (2008b). Rehabilitation of hemianopic dyslexia: Are words necessary for re-learning oculomotor control? *Brain*,. doi:10.1093/brain/awn285

Sommerhalder, J., Oueghlani, E., Bagnoud, M., Leonards, U., Safran, A. B., & Pelizzone, M. (2003). Simulation of artificial vision. I. Eccentric reading of isolated words, and perceptual learning. *Vision Research*, *43*, 269–283.

Sommerhalder, J., Rappaz, B., de Haller, R., Pèrez Fornos, A., Safran, A. B., & Pelizzone, M. (2004). Simulation of artificial vision. II. Eccentric reading of full-page text and the learning of this task. *Vision Research*, *44*, 1693–1706.

Spitzyna, G. A., Wise, R. J. S., McDonald, S. A., Plant, G. T., Kidd, D., Crewes, H., et al. (2007). Optokinetic therapy improves text reading in patients with hemianopic alexia: A controlled trial. *Neurology*, *68*, 1922–1930.

Tant, M. L. M., Cornelissen, F. W., Kooijman, A. C., & Brouwer, W. H. (2002). Hemianopic visual field defects elicit hemianopic scanning. *Vision Research*, *42*, 1339–1348.

Teuber, H.-L., Battersby, W. S., & Bender, M. B. (1960). *Visual field defects after penetrating missile wounds of the brain*. Cambridge, MA: Harvard University Press.

Trauzettel-Klosinski, S., & Brendler, K. (1998). Eye movements in reading with hemianopic field defects: The significance of clinical parameters. *Graefe's Archive for Clinical and Experimental Ophthalmology*, *236*, 91–102.

Wilbrand, H. (1907). Über die makulär-hemianopische Lesestörung und die v. Monakowsche Projektion der Makula auf die Sehsphäre [On the macular-hemianopic reading disorder and the v. Monakowian projection of the macula on the visual sphere]. *Klinische Monatsblätter für Augenheilkunde*, *45*, 1–39.

Wilde, O. (1931). *The works of Oscar Wilde*. London: Collins.

Zangemeister, W. H., & Oechsner, U. (1999). Adaptation to visual field defects with virtual reality scotoma in healthy subjects. In W. Becker, H. Deubel, & T. Mergner (Eds.), *Current oculomotor research* (pp. 89–92). New York: Kluwer.

Zangemeister, W. H., Oechsner, U., & Freska, C. (1995). Short-term adaptation of eye movements in patients with visual hemifield defects indicates high level control of human scanpath. *Optometry and Vision Science*, *72*, 467–477.

Zangemeister, W. H., & Utz, P. (2002). An increase in a virtual hemianopic field defect enhances the efficiency of secondary adaptive gaze strategies. *Current Psychology of Cognition*, *21*, 281–303.

Zhang, X., Kedar, S., Lynn, M. J., Newman, N. J., & Biousse, V. (2006). Homonymous hemianopias: Clinical–anatomic correlations in 904 cases. *Neurology*, *66*, 906–910.

Zihl, J. (1989). Cerebral disturbances of elementary visual functions. In J. W. Brown (Ed.), *Neuropsychology of visual perception* (pp. 35–58). Hillsdale, NJ: Lawrence Erlbaum.

Zihl, J. (1995a). Eye movement patterns in hemianopic dyslexia. *Brain*, *118*, 891–912.

Zihl, J. (1995b). Visual scanning behavior in patients with homonymous hemianopia. *Neuropsychologia*, *33*, 287–303.

Zihl, J. (1999). Oculomotor scanning performance in subjects with homonymous visual field disorders. *Visual Impairment Research*, *1*, 23–31.

Zihl, J. (2000). *Rehabilitation of visual disorders after brain injury*. Hove, UK: Psychology Press.

Zihl, J. (2003). Recovery and rehabilitation of cerebral visual disorders. In M. Fahle & M. W. Greenlee (Eds.), *The neuropsychology of vision* (pp. 319–338). Oxford: Oxford University Press.

Zihl, J., & Hebel, N. (1997). Patterns of oculomotor scanning in patients with unilateral posterior parietal or frontal lobe damage. *Neuropsychologia*, *35*, 893–906.

Zihl, J., & Kennard, C. (1996). Disorders of higher visual function. In T. Brandt, L. R. Caplan, J. Dichgans, H. C. Diener, & C. Kennard (Eds.), *Neurological disorders: Course and treatment* (pp. 201–212). San Diego, CA: Academic Press.